THE IMPLICATIONS OF THE RISE OF CLEAN ENERGY ON LITHIUM MARKET DYNAMICS

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DECLARATION

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ABSTRACT

This research aims to assess the factors surrounding the emergence of markets with the greatest potential for rechargeable lithium battery adoption. The implications of the rise of electric vehicles and electrical energy storage are measured against lithium supply and market pricing. This was resolved by reviewing all available information and comparing it with the intricacies of resources, production and recycling. An analysis of price formation is also undertaken before making assumptions to enable a forecast of future market dynamics until 2030. Electric vehicles will require almost threefold the lithium produced in 2015 by the end of the period considered, with grid storage predicted to follow suit. No geological supply constraints were found, but economic scarcity is a strong possibility. Production is highly vulnerable to disruption due to concentration and the situation is exacerbated by inelastic demand. Recycling may be the most critical means of diversifying and improving supplies.

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LIST OF SYMBOLS

°C	Degrees centigrade
%	Percent
A	Ampere
G	Giga- (1×10^9)
g	Gram
h or hrs	Hour or hours
k	Kilo- (1×10^3)
LCE	Lithium carbonate equivalent
l	Litre
M	Million or mega- (1×10^6)
m	Metre
min	Minute
sec	Second
T	Tera- (1×10^{12})
t	Tonne
toe	Tonne(s) of oil equivalent (equal to 11.63 MWh)
USD	United States Dollar
V	Volt
W	Watt
wt%	Weight percent

LIST OF ACRONYMS

2DS	Two-degree Scenario, as defined by the International Energy Agency, limiting temperature rise to 2 ˚C by 2100.
B2DS	Beyond Two-degree Scenario, as defined by the International Energy Agency.
BEV	Battery electric vehicle
BNEF	Bloomberg New Energy Group
CAES	Compressed air energy storage
CIF	Cost, insurance and freight
DRC	Democratic Republic of Congo
ESS	Energy storage system
EV	Electric vehicle
FMC	Food Machinery Corporation
FOB	Free on board
GDP	Gross domestic product
HEV	Hybrid electric vehicle
ICE	Internal combustion engine
IEA	International Energy Agency
IEC	International Energy Commission
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LCO	Lithium cobalt oxide ($LiCoO_2$) cathode battery technology
LDV	Light-duty vehicle

LFP	Lithium iron phosphate ($LiFePO_4$) cathode battery technology
Li or Li-ion	Lithium-ion battery technology
LiPo	Lithium-ion polymer battery
LME	London Metals Exchange
LMO	Lithium manganese oxide ($LiMn_2O_4$) cathode battery technology
NCA	Lithium nickel cobalt aluminium oxide ($LiNi_{0.80}Co_{0.15}Al_{0.05}O_2$) cathode battery technology
NDC	Nationally determined contribution under the Paris Agreement of the United Nations Framework Convention on Climate Change
NiCd	Nickel Cadmium battery
NiMH	Nickel metal hydride battery technology
NMC	Lithium nickel manganese cobalt oxide ($LiNi_xMn_yCo_{1-x-y}O_2$) cathode battery technology
NPV	Net present value
OECD	Organisation for Economic Co-operation and Development
OICA	Organisation Internationale des Constructeurs d'Automobiles (International Organization of Motor Vehicle Manufacturers)
OPEC	Organization of the Petroleum Exporting Countries
PGM	Platinum group metals
PHEV	Plug-in hybrid electric vehicle
PHS	Pumped hydroelectric storage
REE	Rare-earth elements

RTS	Reference Technology Scenario as defined by the International Energy Agency
SMES	Superconducting magnetic energy storage
SQM	Sociedad Quimica y Minera de Chile
TES	Thermal energy storage
UK	United Kingdom
UN	United Nations
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
UNFCC	United Nations Framework Convention on Climate Change
US DoE	United States Department of Energy
US or USA	United States of America
USGS	United States Geological Survey
VRB	Vanadium redox (flow) battery technology
ZEBRA	Sodium-nickel chloride battery technology
ZnBr	Zinc bromine (flow) battery technology

1 INTRODUCTION

Commercial-scale production of the lithium-ion (Li-ion) battery was introduced in 1991 by Sony Corporation, after being conceived by researchers in Oxford eleven years' previous (Mizushima, Jones, Wiseman and Goodenough, 1980; Yoshino, 2012). Since this development, lithium (Li) battery technology has taken the market by storm, becoming the primary end market for global lithium production (Jaskula, 2017). Diouf and Pode (2015) indicate that the major reason behind this rapid diffusion is its advantages over traditional battery types. Li-ion batteries possess twice the energy density, a relatively high cycle life and energy efficiency and no memory effect when compared to its competitors.

These properties have made Li-ion batteries the clear choice for portable electronics manufacturers, capturing over half the sector in 2015 (Scrosati and Garche, 2010; Macquarie Research, 2016). This remains the largest application, but demand within the electric vehicle (EV) industry is set to overtake this rapidly (Macquarie Research, 2016). Diouf and Pode (2015) argue that while, traditionally, diffusion of Li-ion batteries has been limited by their greater cost, emergence of the EV industry is encouraging research and advances. Industry analysts have shown that prices have fallen by almost two thirds from 2009 to 2016 (Lache, Galves, Nolan, Toulemonde, Gehrke, Sanger, Ha, Rao and Cran, 2008; Macquarie Research, 2016). This is seen as a driving force in the adoption of this technology within the renewable energy sector. Here, energy storage systems (ESS) are required for capturing and redistributing power generated outside of peak demand hours. This may eventually create a market larger than the vehicle sector (Diouf and Pode, 2015).

The question of this research is to quantify and assess lithium supplies and demand with specific focus on applications in clean energy, both at present and in the future. This must be done in order to determine if production will support growth in demand and how market prices might react if it is unable to. If market prices become too high, this could render Li-ion technology excessively expensive for its use in applications of clean energy. The benefit of predicting any market shocks due to supply deficits is the ability to respond by way of levels of production or source diversification. This would avoid the loss of opportunities in reducing global greenhouse gas emissions that lithium batteries can provide.

Some authors have pointed to the geological distribution of lithium and control of its production as a source for serious concern (Maxwell, 2015; Macquarie Research, 2016). Martin, Rentsch, Höck and Bertaqu (2017) suggest that these combined with political and environmental factors within producing countries are major issues in price development. Commonly neglected or avoided in previous studies surrounding this issue are the contributions of recycling to supplies and the demand from the power generation and distribution sector.

This research aims to assess and uncover the factors surrounding the emergence of markets with the greatest potential for rechargeable lithium battery adoption, in EVs and ESS, and to analyse the resultant implications for the lithium market in terms of supply, demand and pricing. To understand these dynamics, the various applications of lithium will first be analysed, placing the markets for lithium batteries in EVs and ESS in context. This will be compared with other competing technologies to ascertain the possibility of substitution while viewing how advances in science and engineering are reducing the intensity of lithium usage.

Following this, the supply side will be assessed in terms of the global resources available, the stakeholders involved in extraction, as well as the possibilities of lithium recycling. Price development will then be discussed, relating how other instances of disruption may apply to the lithium market. Assumptions are made upon this review of all available information before determining the balance of the market until 2030, stating the limits to these findings.

2 THE GROWTH OF CLEAN ENERGY

Ultimately, market pricing cannot be understood by only analysing the sufficiency of geological availability and economic supplies. Henckens, van Ierland, Driessen, and Worrell (2016) explain that demand may increase due to factors such as new technological applications for a material or the industrial development of economies. Alternatively, technology may also substitute one material with another or improve efficiencies in manufacturing, lowering this demand. Stated differently, Roberts (1992) details that the rate of product consumption may be affected by:

1) the material composition of product, or the quantity of material used in each product,
2) the product composition of output, or the portion of the economy devoted to producing that product, and
3) the total size of the economy.

The first factor, material composition of product, may be affected by the mix of technologies producing that product, the material requirements of each of them as well as the possibilities for substitution or efficiencies. Considering this, demand for lithium must first be understood in terms of the array of its applications and assessing which are most likely to have the most impact on consumption. Then, secondly, evaluating any possibilities for substitution of lithium in these applications before finally estimating the rate at which manufacturing efficiencies are occurring, if at all.

2.1 The Applications of Lithium

The application of lithium, a silvery-white metal, in industry is due to several beneficial properties. Its most significant is that it possesses the greatest electrochemical potential of all known metals, while also being the lightest solid element at room temperature (Macquarie Research, 2016). Lithium also imparts high mechanical strength and thermal shock resistance to materials due to a high coefficient of thermal expansion. It is also able to modify viscosity in liquids, as well as having important fluxing and catalytic characteristics (Brown, Walters, Idoine, Gunn, Shaw and Rayner, 2016). This has created a diverse array of industrial applications that can be broadly be categorized into technical and chemical uses, according to Baylis (2013).

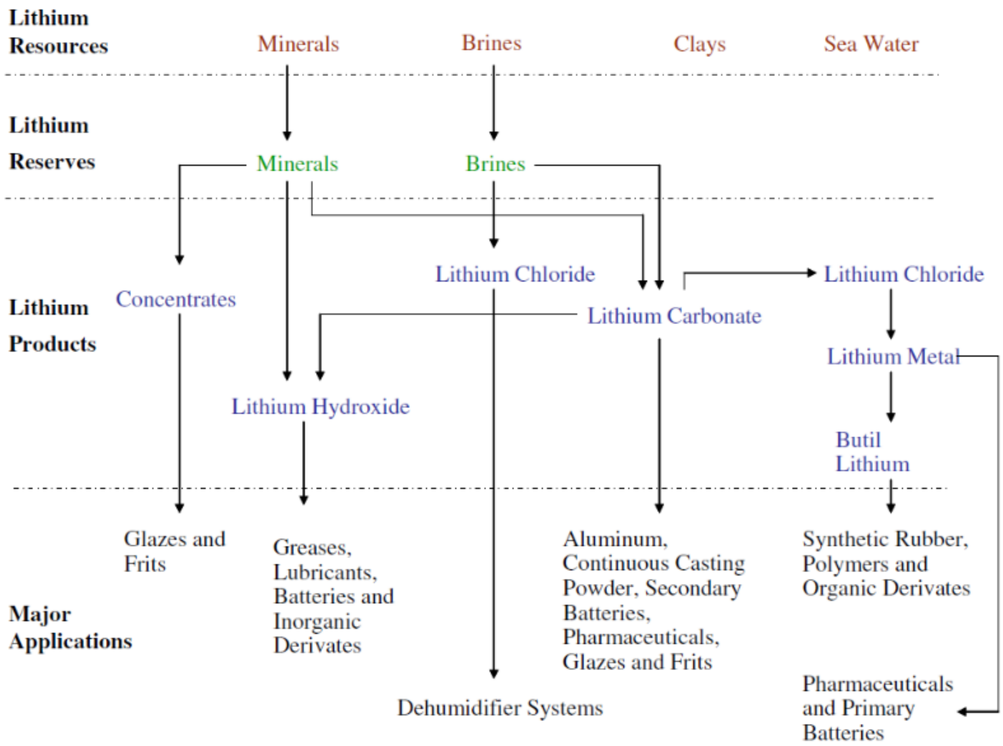

Figure 2.1 Types of lithium resources, reserves, products and major applications (Yaksic and Tilton, 2009).

Over 200 forms of lithium are marketed globally (Evans, 2014), but Yaksic and Tilton (2009) indicate that there are only four first stage products derived from lithium deposits. Mineral concentrates, comprising mostly spodumene, petalite and lepidolite, as well as lithium hydroxide and carbonate are derived from mineral deposits. Lithium brines produce the first-stage chemical products of lithium carbonate and chloride, which are processed further to manufacture hydroxides, chlorides, metal and organolithiums. The flow of these products to their end markets from their various lithium deposits is illustrated in Figure 2.1. Amongst first-stage products, carbonate was the foremost at 49% of production in 2015 while mineral concentrates comprise most of the remaining share at 44% (Macquarie Research, 2016)

The most important application of technical products is in the glass and ceramic industry where it is used in glazes and frits to reduce melting temperatures and increase thermal shock and chemical resistance. This reduces the amount of energy required to maintain glass in a liquid state during manufacturing and creates a far more durable product. Its addition also improves mechanical strength, colourfastness and reduces shrinkage of ceramics (Martin *et al.*, 2017). The glass and ceramic sectors accounted for around 30% of lithium consumption globally in 2016, shown in Figure 2.2 (Jaskula, 2017).

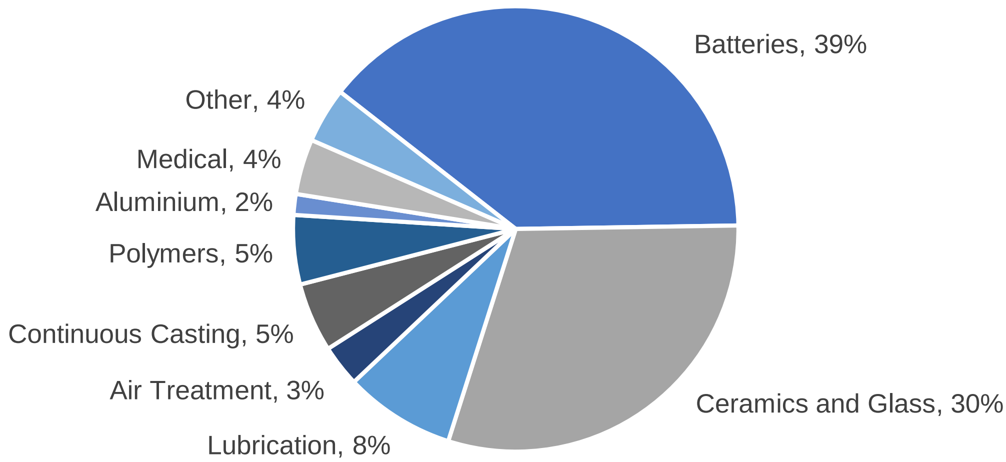

Figure 2.2 The 2016 global market share of lithium products (Jaskula, 2017).

The steel and aluminium industries also require these technical-grade products in metallurgical applications, although in much smaller quantities, requiring about 5 and 2% respectively of the annual production of lithium (Hocking, Kan, Young, Terry and Begleiter, 2016). Steel production uses lithium in casting powders where it reduces defects in continuous casting and acts as a flux, reducing operating inputs. Lithium carbonate is also added to cryolite (NaF) baths in aluminium electrolysis to reduce the melting point and improve viscosity through the conversion to lithium fluoride (Evans, 2014). This reduces electricity consumption by around 2 to 4% and slightly improves degradation of the carbon cathode. The addition of lithium to aluminium-copper alloys produces a high-strength, low weight material that is most commonly used in the fabrication of aircraft (Hocking *et al.*, 2016).

The grade of technical products is lower than in chemical applications and thus lithium carbonate, hydroxide and mineral concentrate of this specification sells for cheaper prices. Iron content in excess of 0.1% is a problem for the glass industry, however, where it can affect clarity (Macquarie Research, 2016). Mineral concentrate, ranging from 1.8 to 3.5% Li (Evans, 2014), may comprise a large proportion of primary production but it also converted to chemical products and it is estimated that only 14% of it is used in its raw form (Hocking *et al.*, 2016). The majority of this concentrate is supplied by Talison's Greenbushes mine in Australia as well as from Bikita in Zimbabwe (Evans, 2014).

Chemical applications require more stringent quality and feed control and overall grades than technical products. Lithium carbonate is by far the most traded compound of these at around half of the market and, for this reason, trade data is often represented in lithium carbonate equivalent (LCE). Lithium hydroxide is the second-most traded product at a fifth of global share, with chlorides, organolithium, pure metal and other lithium compounds making up the remaining 16% (Hocking *et al.*, 2016). The conversion rates and chemical formulae for the most commonly traded forms of lithium are presented in Table 2.1.

Table 2.1 Commonly marketed chemical forms of lithium and conversion rates.

Chemical	**Formula**	**Conversion Factors**		
		Lithium content	**Lithium oxide content**	**Lithium carbonate equivalent**
Lithium	Li	-	2.153	5.323
Lithium oxide	Li_2O	0.464	-	2.473
Lithium carbonate	Li_2CO_3	0.188	0.404	-
Lithium chloride	LiCl	0.163	0.362	0.871
Lithium bromide	LiBr	0.080	0.172	0.425
Lithium hydroxide monohydrate	$LiOH.H_2O$	0.165	0.356	0.880
Butyllithium	C_4H_9Li	0.108	0.233	0.575

Source: (Brown *et al.*, 2016)

In terms of end-use markets, battery production is currently the primary consumer of lithium products at 39% in 2016 (Figure 2.2) (Jaskula, 2017). In its high-grade (99.5%) carbonate and hydroxide form, it is used in the manufacture of rechargeable batteries, where lithium is alloyed with other metals to form the cathode, anode or to act as the electrolyte in the form of Li-salts between the two electrodes (Martin *et al.*, 2017). These secondary batteries are more commonly known as Li-ion and are used in numerous applications from portable electronics to aeronautics. Primary lithium batteries, which are single-use, require pure lithium metal in their anodes to provide exceptional battery life and low weight. However, these are often more expensive than other types of primary batteries (Brown *et al.*, 2016).

Lithium soap is a combination of lithium hydroxide monohydrate and fatty acids that are used to manufacture a wide variety of lubricating greases where it extends operating temperatures and improves water resistance (Evans, 2010). Around 70% of global grease production requires its addition, making up approximately 0.2 to 0.3% of the final product (Hocking *et al.*, 2016). Jaskula (2017) indicates that this formed around 8% of the lithium market in 2016, making it the third most important application.

Anhydrous lithium hydroxide and lithium peroxide are used to scrub carbon dioxide in closed systems such as aircraft or in mines through the conversion to lithium carbonate. Lithium bromide and chloride are also utilized in air treatment, especially in air conditioning, where it removes moisture from the air due to their hygroscopic nature (Brown *et al.*, 2016). This application does not play a significant role in the lithium market due to it accounting for only about 3% of consumption (Jaskula, 2017).

Lithium chloride is also used to produce organolithium compounds, such as butyllithium, that are used as catalysts in the production of synthetic rubber and plastic. The principal application of these products is in car tyre manufacturing but can also be found in a range of other uses, from plastic packaging to golf balls (Hocking *et al.*, 2016). Also referred to as polymers, their production accounts for around 5% of annual lithium usage (Jaskula, 2017). Pharmaceuticals are also derived from lithium chloride for the medical industry, where it is primarily applied in the treatment of bipolar and psychiatric disorders as well as depression and nervous problems (Evans, 2014). This is reported to comprise 4% of global lithium demand according to Hocking *et al.* (2016).

The United States Geological Survey (USGS) provides the most recent estimates of lithium consumption for the year 2016, but this has changed drastically over the past decade, as represented in Figure 2.3 (Ober, 2007; Jaskula, 2017). Its application in batteries has only recently become the primary consumer of lithium, overtaking the ceramics and glass sector in 2016, expanding by 4% (Jaskula, 2016, 2017). The traditionally dominant sector, glasses and ceramics, now accounts for 30% of consumption even though it continues to grow, albeit more slowly than the battery sector (Macquarie Research, 2016; Jaskula, 2017). Lithium use in continuous casting is the only other application that has extended its relative market share over the last ten years, although it remains a minor use (Ober, 2007; Jaskula, 2017).

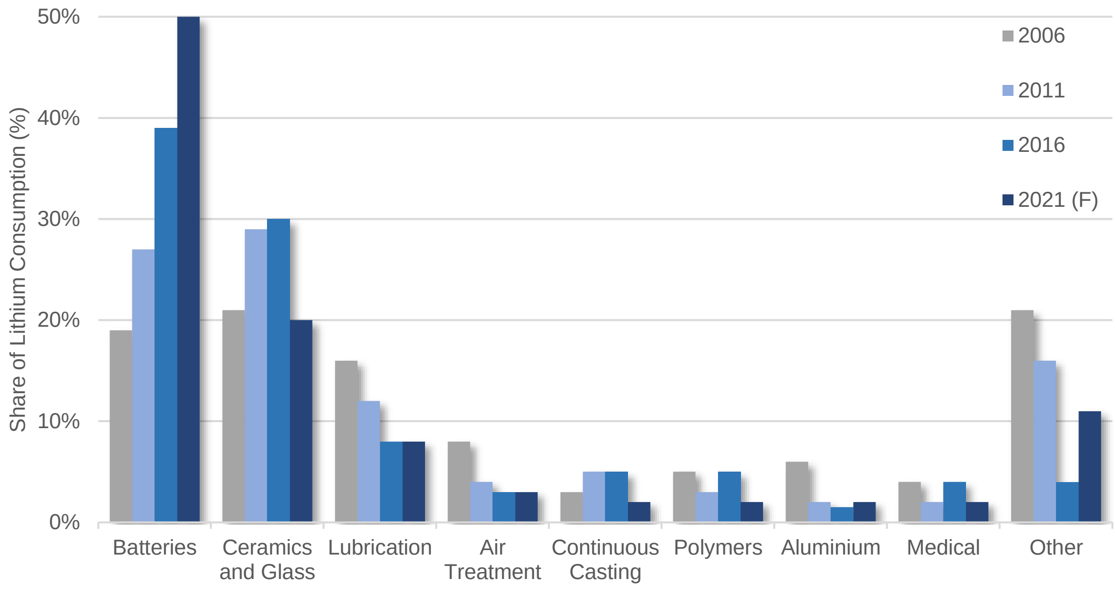

Figure 2.3 Global lithium end-markets since 2006 (Ober, 2007; Jaskula, 2010, 2017) with a forecast for 2021 by Macquarie Research (2016).

Forecasting the demand for lithium by subsector remains difficult due to the rapid rise of its consumption in batteries. Nevertheless, industry analysts at Deutsche Bank (Hocking *et al.*, 2016) and Macquarie Research (2016) indicate that the requirements of the battery market for lithium will rise to 65 and 50% respectively, in the year 2021. The more conservative perspective of Macquarie Research (2016) is presented in Figure 2.3 for comparison with present and past consumption figures. All other subsectors are expected to contract in relative terms, but in terms of tonnes of lithium consumed, every application has been forecasted to grow until 2021.

Both institutes agree that non-battery demands will continue to rise at a rate of up to 4%, or even remain stable in the case of aluminium. The battery sector, however, is predicted to expand lithium consumption at an average of 17% per annum, presenting the greatest potential within the lithium market (Macquarie Research, 2016). This is also confirmed by Gruber, Medina, Keoleian, Kesler, Everson and Wallington (2011) who compared sector consumption from 2006 through 2008 to find that all other applications were contracting relative to the battery market.

2.2 Lithium Battery Technology

The advancement of rechargeable battery technology first allowed the mass adoption of mobile phone technology in the 1990's, as well as the revolution that smartphones and tablets brought to the world at the start of the 21st century (Hocking *et al.*, 2016). Now rechargeable batteries have become capable enough to power our mobility in the form of EVs and may be on its way to enabling and transforming the worlds power generation and distribution (Diouf and Pode, 2015). This section looks at the history of the technology, the working principles behind it, as well as the variations that are available within Li-ion batteries. The various markets of lithium batteries are also analysed with regards to trends and intensity of use before discussing the issues associated with Li-ion batteries.

While the invention of the modern battery occurred in the beginning of the 19th century, credited to Alessandro Volta, a rechargeable battery didn't appear until 1859 (Palacín, 2009; Hocking *et al.*, 2016). This was the development of the lead-acid battery that still dominates the vehicle industry today due to its low cost and robustness (Macquarie Research, 2016). Its low energy density, however, led to a large amount of research into alternate chemistries which produced alkaline, nickel-cadmium (NiCd), nickel-iron and zinc-carbon batteries by the early 20th century (Hocking *et al.*, 2016).

The alkaline battery, which is still common today, went into commercial production in 1959 and nickel-hydrogen and nickel-metal hydride (NiMH) batteries became available 30 years later, in 1989 (Hocking *et al.*, 2016). The latter, NiMH, was a significant development as it had around three times the energy density of lead-acid batteries, allowing its application in new markets. Additionally, it does not possess the toxic metals of cadmium and lead like other technologies (Diouf and Pode, 2015). The majority of hybrid vehicles, such as the Toyota Prius, still use NiMH batteries today (Macquarie Research, 2016).

Around a century ago, Lewis and Keyes (1913) first considered lithium for use as a battery electrode due to its electrochemical potential, but it was it was largely neglected until the 1970's when research by Bell and Exxon Laboratories piqued interest again (Murphy and Trumbore, 1976; Whittingham, 1978). This work was unsuccessful due to considerable cost and safety issues but was helpful in providing a basis for current technology (Blomgren, 2017).

The conception of the Li-ion battery as it is today is often incorrectly attributed to the Goodenough Laboratory for their discovery of the lithium-cobalt cathode ($LiCoO_2$ or LCO) (Mizushima *et al.*, 1980; Blomgren, 2017). This study, however, used lithium metal as the anode which formed dendrites, or needle-like lithium metal particles, to grow between the electrodes and eventually short-circuit the battery. This encouraged research into non-metallic negative electrodes that eventually led to the discovery of graphite and hard-carbon anodes (Nitta, Wu, Lee and Yushin, 2015; Hocking *et al.*, 2016).

The first working prototype of a rechargeable Li-ion battery was demonstrated in 1986 by Yoshino, Sanechika and Nakajima at Asahi Kasei. This had an LCO cathode, a coke anode and non-aqueous electrolytes, the same form as the modern Li-ion battery (Yoshino, 2012). They had created a highly-efficient, high voltage battery that was far more stable than previous iterations and twice the energy density of the next best technology, NiMH. Most importantly, its electromotive force of around 4V made it ideal to power portable electronics (Blomgren, 2017). Sony made the battery commercially available in 1991 and it was subsequently adopted rapidly around the world (Yoshino, 2012).

Rechargeable batteries, in principle, consist of a positive electrode, or cathode, and a negative electrode, or anode, that are separated by an electrolyte that conducts ions, yet insulates electrically (Figure 2.4). When the electrodes, which are made of electrochemically active couples, are connected via an external circuit, electrons are forced to travel to the opposite electrode. Ions balance this exchange by moving across the electrolyte, in the same direction as the flow of electrons, to the other electrode. The loss of electrons and ions results in oxidation, and reduction in the electrode where electrons and ions collect. The flow of electrons, also known as current, will cease as soon as this redox reaction is complete. Rechargeable batteries are unique in that the reaction can be reversed if the current is applied to the electrodes allowing the battery to be recharged (Palacín, 2009).

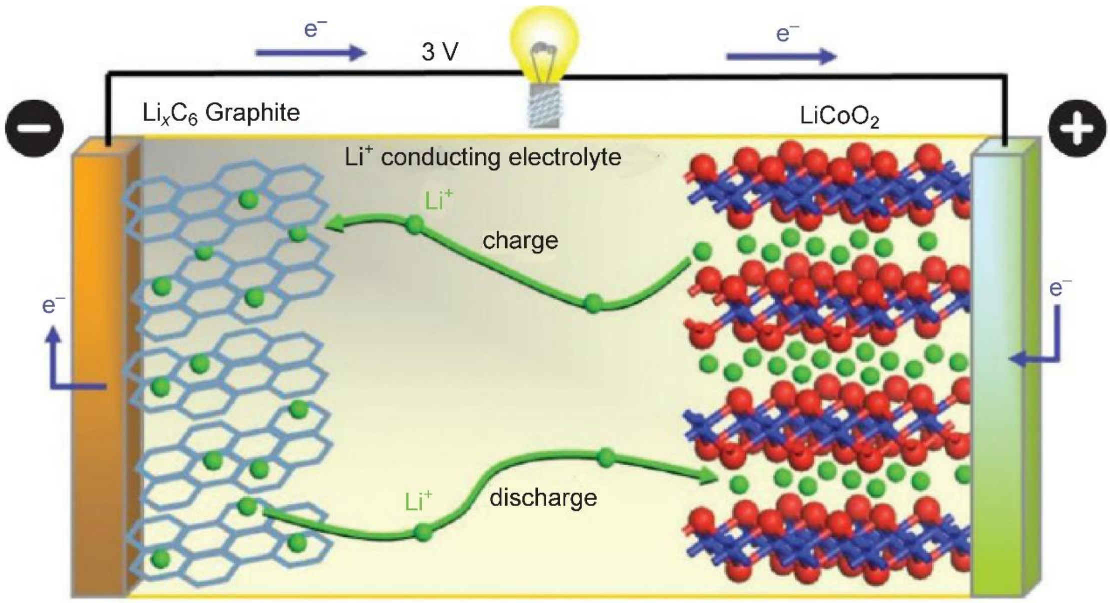

Figure 2.4 Schematic illustration of a Li-ion battery with $LiCoO_2$ cathode and graphite anode (Miller, 2015).

Many redox reactions exist, yet only a few have been exploited commercially. This depends on the specific electrochemical capacity of the electrodes to exchange electrons per atomic weight, expressed as Ah/kg, and the difference in potential between the electrodes, or voltage. The amount of energy, or power, a battery can provide is typically used to compare batteries and is expressed in Wh/kg. In applications where battery size is more important than weight, energy capacity and power may also be expressed in terms of volume, in litres.

Numerous other criteria are considered before determining a battery's suitability, such as cost, safety, cycle life and reliability (Palacín, 2009).

In Li-ion batteries, the anode of choice these days is graphite-based due to its abundance, high conductivity and cycle life, and low cost and potential versus Li. Electrochemical activity is produced by intercalating Li between graphene planes (Nitta *et al.*, 2015). The electrolyte conventionally consists of lithium salt, $LiPF_6$, dissolved in a mixed organic solvent of dimethyl and diethyl carbonate, separated by a microporous polyolefin or polyethylene membrane. An array of different cathode chemistries is available commercially, but lithium-based metal oxides dominate the present market (Palacín, 2009; Blomgren, 2017). The construction of the LCO battery illustrates the working principles of this technology in Figure 2.4.

The earliest form of Li-ion battery was the cylindrical cell and is still the most widespread due to its ease of manufacture and thus lower cost. The most popular size is the "18650", which denotes its width in the first two digits in mm, and its height in the last three in tenths of mm (Blomgren, 2017). Prismatic or rectangular cells, developed in the 1990's, did not differ in composition but satisfied demand in low-profile devices. The development of the pouch cell in 1995 was a major advancement as cells could be tailor-made to fit any device and did not require a metal casing like prismatic or cylindrical cells. These are often marketed as Li-polymer (LiPo) batteries or thin-laminates, which refers to the polymerised, and not liquid, form of the electrolyte and wrapped laminate structure of the electrodes. The electrode chemistry, however, remains identical to that found in other battery forms (Buchmann, 2017).

Five cathodic chemistries dominate the Li-ion market landscape, and these are compared in Table 2.2. The oldest of these, LCO maintains the greatest share at around a third of global sales in 2015, as estimated by Macquarie Research (2016). Although it has good cycle life and energy density, it possesses low thermal stability and is expensive due to 60% of its makeup being cobalt. Nevertheless, it is commonly found in portable electronics such as laptops and phones (Macquarie Research, 2016). The second-most popular cathode is NMC which has rapidly gained this share due to its application in both high energy and high-power uses, as well as its ease of manufacturing. Blomgren (2017) also mentions, however, that NMC patents are currently under dispute, making this its only drawback.

Table 2.2 Comparison of Li-ion battery cathodes.

Cathode	Compound	Specific Capacity (Ah/kg)	Nominal Voltage (V)	Market Share (2015)	Li Content	Characteristics
LCO	$LiCoO_2$	155	3.9	34%	7.1%	Low thermal stability, expensive but good energy capacity.
NMC	$LiNi_xMn_yCo_{1-x-y}O_2$	160	3.8	23%	7.2%	Excellent all-round characteristics but has patent issues.
LMO	$LiMn_2O_4$	100 - 120	4.0	21%	3.8%	Inexpensive and stable but low energy and cycle life.
LFP	$LiFePO_4$	160	3.4	12%	4.4%	Low energy but great cycle life and thermal stability.
NCA	$LiNi_{0.80}Co_{0.15}Al_{0.05}O_2$	180	3.7	9%	7.0%	Excellent capacity and power but has safety concerns.

Source: (Macquarie Research, 2016; Blomgren, 2017)

Both LFP and LMO are well known for their excellent thermal stability and thus safety, but LFP's cycle life is significantly better and provides greater capacity, although at a lower potential (Nitta *et al.*, 2015). The smallest portion of the market, NCA, is viewed as particularly useful in more premium applications where the best capacity at a high power is required. This comes at the cost of poor cycle life and one of the highest prices (Blomgren, 2017). Every version of the Li-ion battery has its advantages and disadvantages that must be weighed according to its application.

Macquarie Research (2016) provides a recent breakdown of the lithium consumption figures regarding the different demands of lithium batteries. From Figure 2.5, it can be seen that primary, non-rechargeable batteries comprise only 7% of the total market, while portable electronics and EVs dominate the rechargeable, or secondary, battery sector at 43% and 33% respectively. However, this snapshot hides the rapid changes that the market is undergoing, which is of more interest when considering future demands.

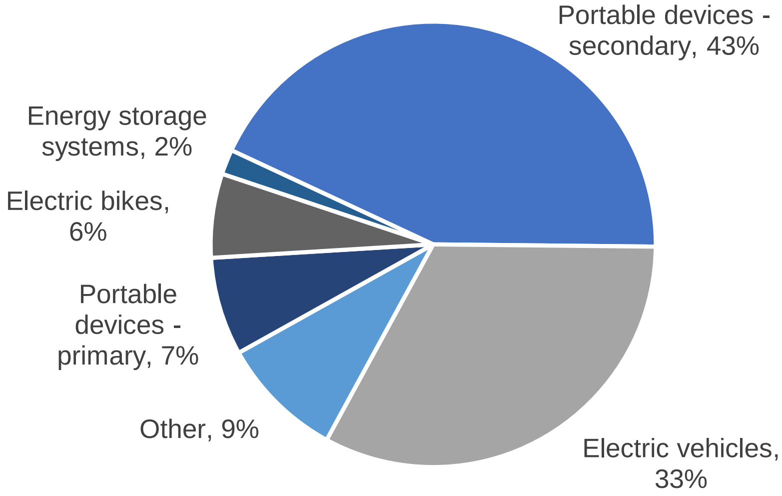

Figure 2.5 Lithium battery demand by sector for 2015 (Macquarie Research, 2016).

In the applications of electric bikes, primary batteries in portable electronics and other technologies, stable increases of 3 to 5% growth were seen from 2014 to 2015. Secondary battery usage in portable devices contracted almost 3% during the same period, in terms of lithium tonnage. Demand from all other EVs, however, more than doubled and applications in electrical storage systems increased by 35% (Macquarie Research, 2016). Industry analysts at Deutsche Bank agree that these two sub-sectors will grow significantly faster than all others in the next five to ten years (Hocking *et al.*, 2016).

This highlights that, although lithium battery usage in portable electronics, such as power tools and mobile phones, is widespread, it may have reached market saturation and demand will only grow proportionately to the growth of those markets. The newer markets of EVs and electrical energy storage systems have only just started to be penetrated and have a greater potential upside (Hocking *et al.*, 2016; Macquarie Research, 2016).

As industry analysts state, Li-ion technology is unmatched when it comes to rechargeable batteries, but two concerns have held them back from widespread adoption in the past (Macquarie Research, 2016). Diouf and Pode (2015) report that Li-ion chemistry needs to become safer as well as more cost-competitive. It is true that it has a poor track record when it comes to safety. In the transport sector alone, over 150 incidents on flights have been attributed to lithium batteries since 1991 and numerous EV fires have been reported in the last 5 years (Federal Aviation Administration, 2017; Mauger and Julien, 2017).

Abada, Marlair, Lecocq, Petit, Sauvant-Moynot and Huet (2016) indicate that failure of these batteries may occur either by short-circuiting or due to thermal runaway. The first may be caused by the formation of metal dendrites from impurities within the battery electrolyte over successive cycles that could pierce the separator and connect the electrodes. This has also occurred by physical means when the battery pack is punctured and often leads to venting of gases and even fire (Abada *et al.*, 2016; Mauger and Julien, 2017). The second mechanism, thermal runaway, occurs when the cell temperature increases beyond a critical point, around 220˚C, resulting in rapid degradation of the cathode and often catastrophic fire (Mauger and Julien, 2017).

Various devices are adopted in Li-ion batteries to prevent this and are often mandatory in manufacturing, such as polyolefin separators that melt beyond 130 ˚C, shutting down the battery before it reaches critical temperatures (Abada *et al.*, 2016). Also required are safety vents, positive temperature coefficient elements and internal protection circuits (Nishi, 2001; Mauger and Julien, 2017). While these precautions are successful in providing a safe battery, inferior manufacturing standards have still lead to recent failures, such as in the case of the large-scale recall of Samsung Galaxy Note devices in 2016 (Mauger and Julien, 2017).

Rechargeable lithium batteries have historically been exorbitantly expensive, which Diouf and Pode (2015) suggest is one of the major reasons slowing their uptake in higher intensity applications. However, many battery producers have expanded manufacturing capacity creating greater economies of scale in addition to manufacturing efficiencies. As a result, analysts indicate that prices have fallen from USD 900 to USD 1000 per kWh in 2010 to around USD 250 per kWh in 2016, a decrease of approximately 75% (Hocking *et al.*, 2016; Macquarie Research, 2016; BNEF, 2017b). Berckmans, Messagie, Smekens, Omar, Vanhaverbeke and Van Mierlo (2017) confirm this rapid decrease in cost, estimating that this technology will pass the USD 100/kWh barrier between 2020 and 2025. This trend will allow a wider variety of applications where their competitiveness in terms of price meant that Li-ion batteries were previously disregarded (Diouf and Pode, 2015).

2.3 Macroeconomic Factors

To place following chapters of the EV and ESS markets into perspective, a quantification of world growth indicators must be made. This provides an assessment of the future of global economic output, which is a vital factor in the calculation of material consumption according to Roberts (1992). Predictions of economic and population growth will also allow an understanding of broader macroeconomic factors involved and will enable a more accurate estimation of the growth of these product markets.

With regards to population estimates, figures from The World Bank and United Nations (UN) are very similar, indicating a total population of 7.3 billion people in 2015 (United Nations, 2017; World Bank, 2017). At least two-thirds of this population resides in Asia and Sub-Saharan Africa, which is predominantly comprised of either developing or transitional nations as defined by the UN. Forecasts of population growth are revised annually but have a low degree of accuracy for long time horizons. By the year 2100, for example, population figures could be as low as 7.2 billion and as high as 16.5 billion due to a multitude of factors, such as migration, birth and mortality rates. The moderate estimate for a shorter term, however, predicts that 8.5 and 9.7 billion people will be around in the years 2030 and 2050 respectively (United Nations, 2017).

The World Bank (2017) put the global gross domestic product (GDP) at USD 74.5 trillion in 2015. The world’s largest emerging market economies, China, India, Indonesia, Brazil, Russia, Mexico and Turkey, also known as the E7, have been expanding at a rate of over 5.8% per year since 2000. In contrast, the G7, the most advanced economies of the United States (US), United Kingdom (UK), France, Germany, Japan, Canada and Italy, have only grown at a rate of 1.8%. This difference has resulted in the E7 markets growing from half the size of the

G7 in 1995 to roughly the same size in 2015 (Hawksworth, Audino and Clarry, 2017).

Analysts at the Organisation for Economic Co-operation and Development (OECD) (2016) predict that the world's economy will continue to expand, albeit at a slowing rate, to USD 111 trillion in 2030 and to USD 182 trillion in 2050. Data on the future of the world's economy is limited, but Hawksworth *et al.* (2017) agree with these figures indicating that the GDP will double by 2042. The distribution of this wealth is highly skewed and most apparent when viewed on a per capita basis. The OECD nations, for example, earn an average of USD 36 741 per capita, according to World Bank data (2017), significantly above the global average of around USD 10 000. Thus, this 35 member group originally formed to stimulate economic progress, is often referred to a club of the rich (Mahon and McBride, 2009).

This has interesting implications for expected material requirements of growing economies of the rest of the world. The theory of material intensity of use was established by the World Steel and Iron Institute in 1972 and furthered by Malenbaum (1973, 1978). The theory describes that the intensity of metal use is closely linked to the level of development of a country as reflected by per capita product, seen for zinc use in the US in Figure 2.6. As a country moves from an agrarian-based economy into industry and construction, material requirements rise rapidly due to the demand for infrastructure. This will continue until the economy shifts from manufacturing to services, such as education, finance and business. These functions are significantly less material intensive while the national product continues to grow (Malenbaum, 1978; Tilton and Guzmán, 2016).

This is closely related to Kuznets curve that predicts the rise and fall of income inequality as GDP increases and has also been applied to environmental pressure (Kuznets, 1955; Grossman and Krueger, 1991). Various studies have shown this to be true, such as in the case of copper in Japan (Guzmán, Nishiyama and Tilton, 2005) and aluminium in Brazil (Suslick and Harris, 1990). Illustrated in Figure 2.6 by zinc use, the largest growth in per capita consumption of metals should be expected around USD 10 000 per capita (Tilton and Guzmán, 2016), which is the current global average GDP. Therefore, the global economy is expected to become far more material intensive in the next few decades as developing countries become wealthier.

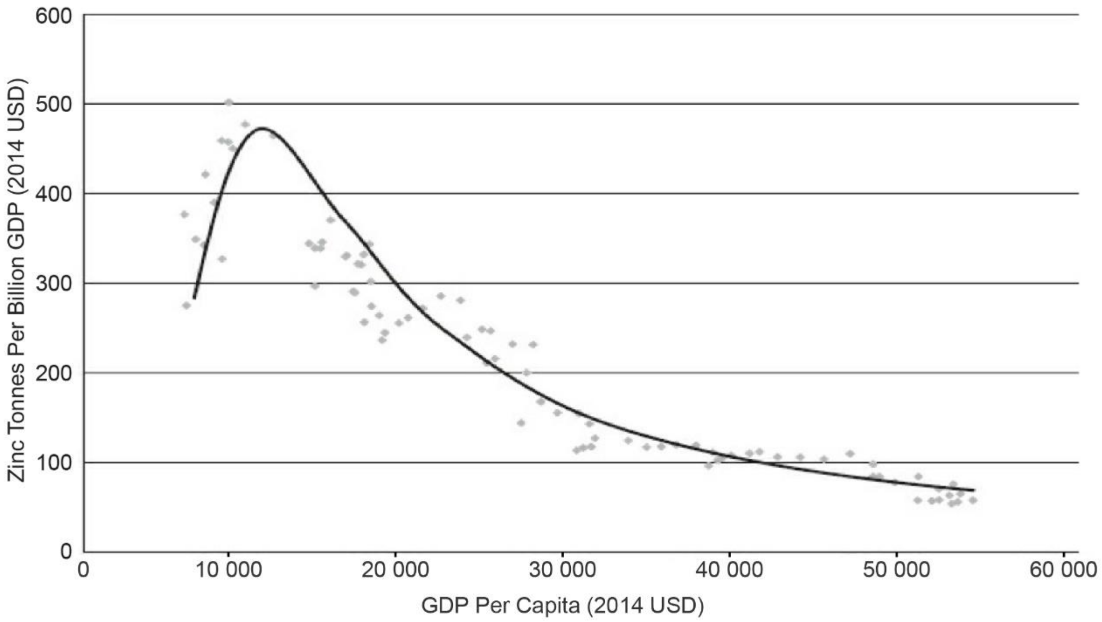

Figure 2.6 Zinc intensity of use (tonnes per billion USD GDP) in the United States between 1929 and 2014 against GDP per capita (USD) (Tilton and Guzmán, 2016).

However, different metals do not follow the same consumption patterns due to their diversity of applications, as Patiño Douce (2016) found. Gold and silver, for example, have not changed markedly as their main use is in the accumulation of wealth such as jewellery and for investment. On the other end of the spectrum, metals that are applied in high-tech uses such as aircraft manufacturing or oil refining are referred to as “group 1” metals. These saw a dramatic rise in per capita consumption in the 20th century.

Lithium also falls into group 1, along with aluminium, cobalt and chromium, and this has strong implications for its future intensity of use. While per capita use of iron, copper and zinc, for example, has slowed and even declined for industrialized nations, the greatest growth of lithium intensity is ascribed to highly developed economies. Thus, he points out that the greatest rise in consumption per capita should be expected of group 1 metals as GDP per capita increases and economies advance technologically (Patiño Douce, 2016). So, even as the global economy is predicted to become more material intensive, metals such as lithium should see the largest growth in consumption rates as the world's population and wealth increase.

This theory has its caveats, however. As Tilton and Guzmán (2016) describe, technological improvements that create efficiencies shift the curve downwards, while innovations that result in substitution and new applications push the curve upwards. These potential shifts are the reason why this hypothesis is not commonly used for material usage predictions. Instead, the material composition of product and the product composition of output, or GDP, are collected and assessed for future changes. It does, however, indicate that an increase in GDP per capita will result in a decline in material intensity in developed nations and a rapid increase in developing economies (Tilton and Guzmán, 2016).

2.4 Electric Vehicles

The EV sector itself has a large range of options when it comes to the type of technology adopted and this will have a major impact on how much lithium is used. The batteries of each of these vehicles needs to replace the energy that is normally derived by the combustion of a fossil fuel, as is done in conventional internal combustion engines (ICEs). An analysis of the principles and capabilities of each design will be undertaken within this section. After which a survey of the EV market, the factors that influence its size, battery intensity and life, and recent trends in mobility will be provided.

Hocking *et al.* (2016) present a thorough review of the technologies currently in use. Hybrid electric vehicles (HEVs) combine the traditional technology of ICEs with electrical feedback and propulsion systems, negating the need to charge the vehicle's battery from an external source. Instead, the battery is charged by both the ICE and regenerative braking. Micro-hybrids offer the lowest level of electrical assistance in propulsion and allow the vehicle's engine to turn off when idling, resulting in 3 to 7% gains in fuel efficiency.

Mild HEVs contain electrical motors and larger batteries that also aid in acceleration. This creates efficiency gains of between 9 and 13% and allows for smaller ICE capacities than typical vehicles. Full HEVs possess electrical systems capable of providing independent propulsion for short distances, such as in Toyota's Prius. These vehicles are typically heavier than ICE cars due to the large electric motor but still provide 22 to 25% improvements in fuel efficiency (Hocking *et al.*, 2016).

Amongst the literature, non-plug-in HEVs are generally not considered to be part of the EV fleet for a few reasons. Firstly, they operate primarily on an ICEs and thus do not require batteries much larger than a single kWh (Gruber *et al.*, 2011; Evans, 2014). Secondly, the majority of the batteries used in HEVs today are NiMH as they do not require high-density energy storage, although they are predicted to be around 75% Li-ion by 2021 (Macquarie Research, 2016). Finally, conventional HEVs no longer qualify for subsidies and tax incentives as they present a far greater impact on the environment. For this reason, the International Energy Agency (IEA) (2017c) considers them to play a negligible role in the future of the vehicle industry.

Plug-in hybrid electric vehicles (PHEVs) operate on the same principles of HEVs but can drive a typical daily distance on electric power alone before the ICE is used. This means that most of the energy consumed will be derived external electricity sources and it is expected that these will produce around 60% efficiencies in fuel economy over traditional vehicles (Hocking *et al.*, 2016). Berckmans *et al.* (2017) provide a survey of the most popular PHEVs sold in Europe in 2016 and surmises that a median battery energy content and electric range for this segment is 9 kWh and 41 km respectively. This is a promising technology as it acts as a transition to fully EVs which are more expensive and still have limited ranges on average (BNEF, 2017a).

Full battery electric vehicles (BEVs) are propelled exclusively by electric motors and do not require any fuel combustion. This presents its greatest advantage, zero-emissions, but it also translates to significantly lower operating costs. Grid power is drastically cheaper than fossil fuels in addition to BEVs requiring far less maintenance. This stems from the fact that fully electric drivetrains only contain a single moving part compared 400 in most ICEs (Bansal, 2015; Hocking *et al.*, 2016). However, there are several disadvantages, as mentioned already, as they tend to be more expensive than ICE vehicles at present and have shorter ranges (Wolfram and Lutsey, 2016).

Berckmans *et al.* (2017) found that the mean energy content and range for small BEVs was 18.2 kWh and 153 km, while the median for medium to large BEVs was 24.2 kWh and 190 km in 2016. Outliers with ranges more than 480 km are the Tesla models, but Wolfram and Lutsey (2016) indicate that battery packs determine up to 86% of manufacturing costs in these extended range vehicles. In the past, this has translated into either limited capacity BEVs or uncompetitive pricing when compared to ICE vehicles. However, analysts agree that BEVs will bridge this price disparity in the early half of the next decade due to the rapidly decreasing costs of batteries (Hocking *et al.*, 2016; BNEF, 2017a).

Somewhat linked to range anxiety is the concern that BEVs take far longer to charge than to than to refill an ICE vehicle with fuel. The IEA (2017c) reports that most drivers still rely on domestic charging facilities which are capable of providing a full charge overnight. A study conducted on the daily driving habits of US drivers by Needell, McNerney, Chang and Trancik (2016) found that this charge would be sufficient in 87% of scenarios when considering a typical BEV in 2013, with a capacity of 19.2 kWh and 117 km range. Longer range vehicles, such as the 75kWh Tesla Model S, would satisfy greater than 99% of daily driving needs without requiring a recharge (Needell *et al.*, 2016; Berckmans *et al.*, 2017). Furthermore, the same study suggests that the remainder of trips could be covered by renting a vehicle that allows for greater range or faster charging. This means that it would be rare for BEV drivers to require a recharge over the course of a day.

Of course, the ideal situation is that BEVs would be able to recharge in the same amount of time that ICE vehicles currently take, which is about five minutes (Kempton, 2016). The implementation of fast direct-current charging technology allows for up to 150 kW at CHAdeMO and Tesla chargers (IEA, 2017c). In practical terms, this equates to a 50% charge in 13 minutes for a Volkswagen e-UP!, and 18 minutes for a Kia Soul EV, both typical BEVs on the market at present. An 80% charge wouldn't take much longer either, at 26 minutes and 36 minutes respectively (Berckmans *et al.*, 2017; Leccy, 2017).

The IEA (2017c) indicates that these fast chargers comprise approximately 34% of the global charger stock of over two million charging points, growing at a rate 72% in 2016. These factors suggest that although BEV range and charging time are a concern to buyers, the technology is already sufficient for most drivers and will likely improve.

As Roberts (1992) illustrated, one of the factors required in estimating the demands of material consumption is the product composition of output. When applied to the EV sector, this would be their proportion within the entire vehicle market. This may be stated either in terms of the number of vehicles on the road, also referred to as global vehicle stock, or, perhaps more relevant, the number of vehicles sold annually.

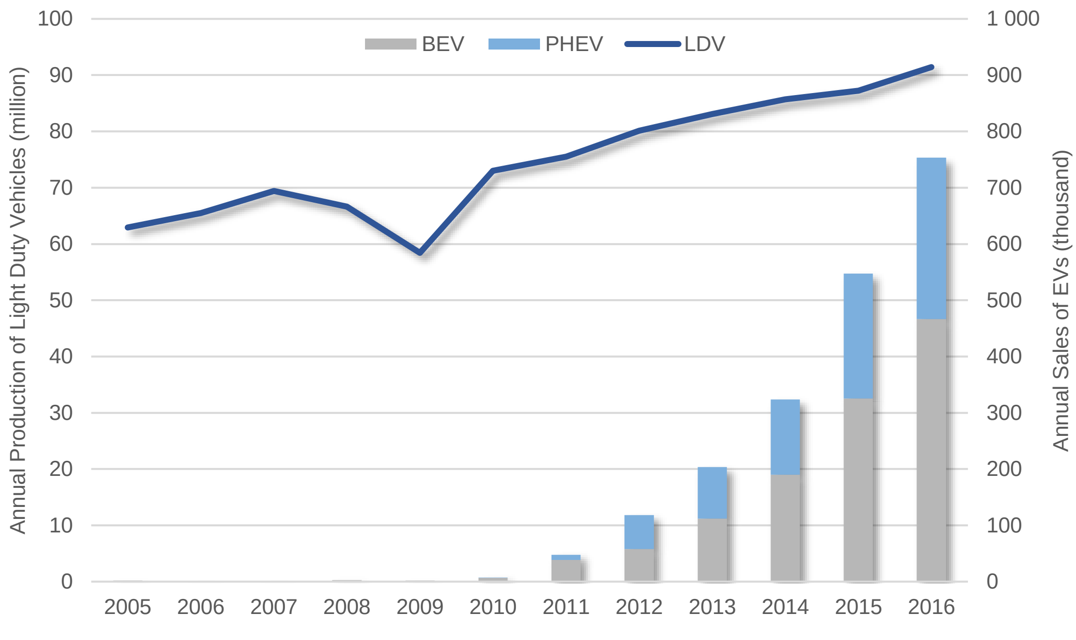

Figure 2.7 Annual production of light-duty vehicles and sales of EVs between 2005 and 2016 (derived from IEA, 2017a, OICA, 2017).

The IEA (2017c) keeps track of sales of global EVs by compiling manufacturer and governmental data and illustrates that diffusion of this technology has been exponential, as seen in Figure 2.7. In a recent report, the institute estimates that over two million EVs were on the world's roads in 2016. Sales in the same year were approximately 753 thousand, of which pure BEVs comprised around 62% and PHEVs were the remaining 38% (IEA, 2017c). This is an average growth rate of 77% over the last five years, although gradually slowing, confirming estimates from industry analysts at Macquarie Research (2016).

When compared with annual production data from the International Organisation of Motor Vehicle Manufacturers (OICA) (2017), it is clear that the EV market has room to grow. Over 90 million light-duty vehicles (LDVs) were manufactured in 2016, which includes passenger and light commercial vehicles, and has expanded at an average of 4% in the last 5 years. Calculations of the global passenger vehicle stock were made by Hao, Geng and Sarkis (2016), derived from a variety of industry sources that are not publicly available, determining that approximately 888 million passenger vehicles were on the world's roads in 2014. OICA (2017) provides more recent data as well as a quantification of the commercial vehicle sector. Over 947 million passenger vehicles were registered in 2015, with an additional 335 million commercial vehicles, for a combined total of 1.282 billion vehicles globally. Conventional ICE vehicles may still represent the clear majority of this, over 99.9%, but it is quickly changing.

Table 2.3 Comparison of estimates for total annual sales of electric LDVs (BEV and PHEV).

Source	Study Date	By Year		
		2020	2025	2030
Berckmans *et al.*	2017	5.1	17.3	36.4
Bloomberg New Energy Finance (BNEF)	2017	2.6	7.6	25.0
KPMG International	2017	6.2	-	-
Hocking *et al.*	2016	2.6	6.9	-
Lukoil	2016	2.5	9.1	23.0
Berret *et al.*	2016	6.2	24.9	-
Boggia	2015	3	-	-
IEA	2011	6.9	17.7	33.3

Source: Various studies indicated above.

A comparison of estimates for sales of electric light-duty vehicles (LDVs) from industry analysts and academia has been compiled in Table 2.3. Predictions vary drastically even for the year 2020, from 2.5 to 6.9 million to between 23 and 36 million for 2030 (IEA, 2011; Lukoil, 2016; Berckmans *et al.*, 2017). However, few authors provide forecasts beyond the next five to ten years with most remaining cautious to extend their view (Boggia, 2015; Berret, Mogge, Schlick, Söndermann and Schmidt, 2016; Hocking *et al.*, 2016; KPMG International, 2017). The volatility of emerging markets for new technologies such as EVs makes market penetration difficult to forecast, but producer ambitions may provide the most reliable indicator. The IEA (2017c) collected announcements of targets from 35 different producers and calculated that 9 to 20 million EVs would be on the roads in 2020, and 40 to 70 million in 2025.

LDVs may form the largest portion of the vehicle market but it does not include large buses and trucks. OICA (2017) reports that 3.85 million of these units were produced in 2016, but while their market share may be insignificant in contrast, heavy vehicles are significantly more energy intensive. The smallest share of the global market, buses at only 0.3%, is undergoing rapid electrification with many major cities already committed to converting their existing public transport buses (Hall, Moultak and Lutsey, 2017). Lukoil (2016) suggests that the technology for electric trucks is not developed enough to see widespread sales, although it predicts sales will reach around 9% of the market in 2030. The IEA (2017c) does not report on the sales of heavy electric trucks.

Hocking *et al.* (2016) provide insight on a sector often not considered in global vehicle sales. Electric bikes and three-wheelers (e-bikes) saw sales of 22 and 8 million units respectively in 2015. While these are normally powered by lead-acid batteries, they suggest the e-bike market will be fully converted to Li-ion by 2023, and 80% of three-wheelers bikes will be converted by 2025. Battery capacities are typically 1 kWh for e-bikes and between 4 and 12 kWh for three-wheelers. Data collation tends to be problematic for this sector but it is clear that China is the dominant market force (IEA, 2017c).

In the same manner that the world’s wealth is heavily skewed towards developed nations, vehicle ownership is too. The positive relationship between GDP per capita and rate of motorization has been studied extensively (Button, Ngoe, and Hine, 1993; Dargay, Gately and Sommer, 2007; Hao, Wang and Yi, 2011; Lu, Ma, Sun and Wang, 2017), and is apparent in OICA’s (2017) statistics regarding registered vehicles per country. The US is by far the most vehicle intensive with 821 vehicles per thousand capita, vastly more than China's 118 and Africa's 42 vehicles per thousand capita.

Dargay *et al.* (2007) go a step further and link levels of urbanisation and population density to lower vehicle saturation levels due to the availability of public transport systems. This provides an explanation as to why a country such as Hong Kong has only 93 vehicles per thousand capita despite it having a similar GDP per capita to the US (OICA, 2017; World Bank, 2017). The study correlates the historical vehicle ownership growth rates of developed nations with a Gompertz curve. This is a sigmoidal, or s-curve, function that predicts the slowest growth at the beginning and end of the period, with the latter half approached slower than the first half. This is applied to global vehicle ownership in order to forecast growth of the vehicle market, as represented in Figure 2.8 (Dargay *et al.*, 2007).

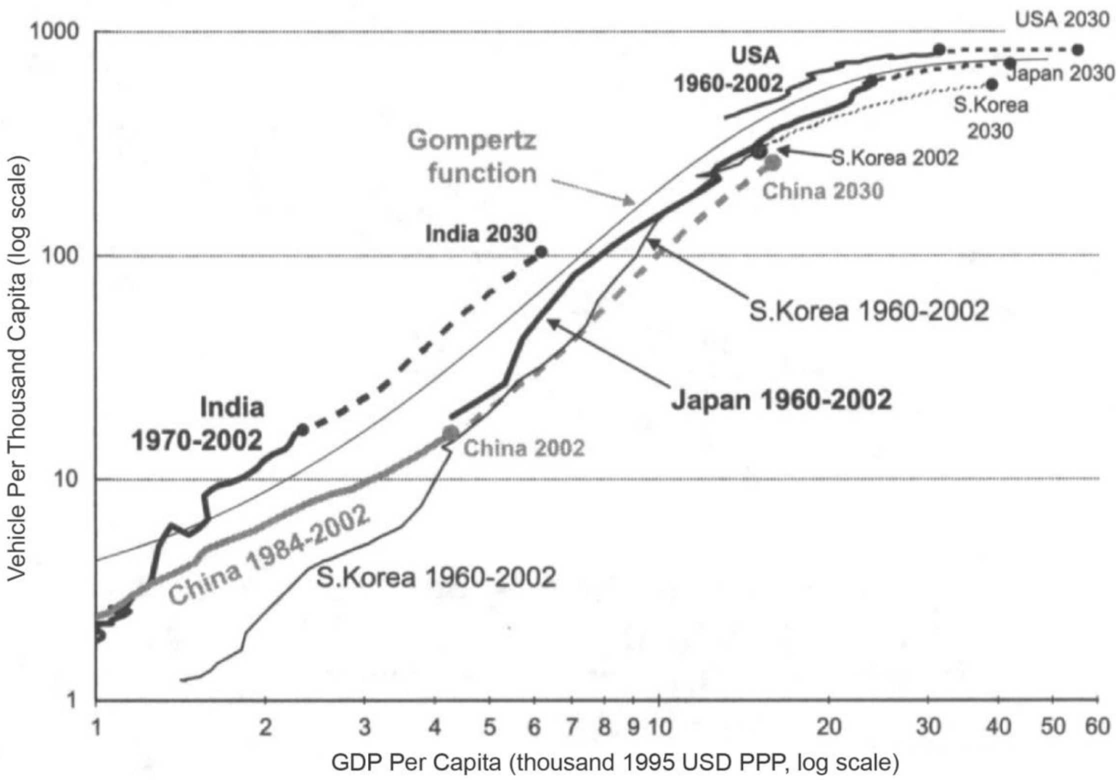

Figure 2.8 Historical vehicle ownership against GDP per capita for the USA, Japan, S. Korea, China and India and as predicted until 2030 by the Gompertz function (Dargay *et al.*, 2007).

Their most significant findings were that increases in vehicle ownership are greatest between USD3 000 and USD10 000 per capita, at a rate of twice the growth of GDP/capita. Beyond that, until USD20 000 capita, ownership only increases at roughly the same rate as GDP/capita. Thus, they predict that most OECD nations are close to saturation levels, and China will more than double their vehicle stock to 390 million by the year 2030. Their forecast for the global fleet is in excess of 2 billion for the same period, approximately 800 million more than are were on the roads in 2016 (Dargay *et al.*, 2007; OICA, 2017).

Predictions of future sales of vehicles are based on historical trade data and but it only provides a reliable estimate if business continues as normal. Several analysts point out that the vehicle industry is ripe for disruption by trends that are already emerging. The first is referred to as mobility services, such as Uber or Lyft, which allows for ride-hailing from a smartphone application and has seen widespread adoption. This may already be lowering the demand for private vehicles but a lack of data means that evidence is still anecdotal (Spulber and Dennis, 2016).

Hops (2016) indicates that these services are already shifting to sharing of private vehicles, citing that the average passenger vehicle is only utilized 4% of the time. It is suggested that this will significantly affect the growth of car sales from about 4% at present to 2% in 2030. Also estimated is that one in ten car sales in 2030 will be purposed as a shared vehicle (Mohr, Muller, Krieg, Gao, Kaas, Krieger and Hensley, 2013). The third development is vehicle automation, which will only become widely available beyond 2020 but may represent 15% of sales in 2030 according to Gao, Kaas, Mohr and Wee (2016). This will support the emergence of ride-hailing and sharing services and lead to lower overall demand for vehicle ownership (Chan, 2017). Many studies on future vehicle demand neglect to consider these trends, although this will only affect the eventual saturation level of the market. At around 1% of present sales, the EV market is not likely to be impacted by this before 2030.

The practical lifetime of batteries in EVs is also an important factor when considering the demand for lithium, as these will inevitably need to be replaced due to capacity degradation (Kushnir and Sandén, 2012). This not only impacts when new batteries will be required but also when these used batteries will be available for reuse and recycling as well. The industry standard is to provide an eight to ten year or 160 to 200 thousand km warranty on the battery pack, as seen for typical BEV models (BMW, 2017; KIA, 2017; Tesla, 2017).

Warranties protect degradation to between 70 and 80% of initial capacity, but surveys of existing use of the Tesla Model S indicates that this degree of degradation only occurs beyond 300 thousand kilometres (Plug-in America, 2017). Lagowski (2017) reports that battery life is negatively affected by high temperatures, overcharging or high voltage, deep discharges or low voltage and high discharges or charge current. Battery lifetime may be difficult to predict at this stage of adoption, but 10 years is a cautious estimate. This figure is also used by studies undertaken by Yaksic and Tilton (2009), Gruber *et al.* (2011) and Kushnir and Sandén (2012).

2.5 Energy Storage Systems

As Dunn, Kamath and Tarascon (2011) state, ESS for national power grids is often seen as the “Holy Grail” for the electric utility industry. This panacea could solve the myriad of problems facing the suppliers of electricity to the world’s growing population. The greatest issue at present is that electricity must be consumed as fast as it is produced, as well as generated adequately to meet demand. In the former situation, power will be lost if it cannot be stored, and in the latter, consumers will be left without power if utilities cannot ramp up generation quick enough. Thus, the capacity of power infrastructure must be great enough to provide during peak demand periods, but most of this will remain redundant each day (Dunn *et al.*, 2011).

Ramping power generation up and down to meet daily demand creates inefficiencies in fuel consumption, higher emissions and greater equipment deterioration, reducing the lifetime of facilities (IEA, 2010). ESS enables the disassociation of electricity supply and demand, overcoming these issues and also only requiring investment aimed at average energy requirements instead of peak energy demand (Dunn *et al.*, 2011). Effectively, this extra capacity during peak periods of demand also has the ability to defer upgrades to the transmission and distribution infrastructure (International Electrotechnical Commission (IEC), 2011).

This role may be referred to as bulk (seasonal) storage, energy time-shift, peak shaving or load-levelling. In essence, all of these functions allow the transfer of load and power generation periods, or energy management, but may be required within seconds up to even a seasonal scale (Luo, Wang, Dooner and Clarke, 2014; World Energy Council, 2016). Often viewed as a separate application, although in the same vein, ESS is also required for the integration of renewable energy sources. Electricity produced from wind farms and photovoltaics is intermittent in nature as they are reliant on variable solar and wind energy. Storage systems bridge the gap between daylight hours and when the wind is driving the turbines, allowing these sources to become more reliable (Diaz de la Rubia, Klein, Shaffer, Kim and Lovric, 2015; World Energy Council, 2016).

ESS may also be utilized in various ancillary applications for operational support aimed at improving reliability and quality of electricity supply. Frequency and voltage disruptions occur on a very short timescale due to inconsistencies in supply and consumption. Storage can counteract this by charging during surges and discharging during dips resulting in a more regular supply (IEC, 2011; Hocking *et al.*, 2016). Support may also be provided in the form of a standing power reserve when generation or the electrical grid fails to meet demand. This is typically only required for up to hour but is required to respond rapidly to ensure a continuous supply in an emergency. Systems that protect from complete failure are referred to as black start support (Luo *et al.*, 2014; Hocking *et al.*, 2016).

There are numerous engineering solutions to ESS that fall into five broad categories (Figure 2.9), according to the IEC (2011) and Deloitte (2015). The most traditional and prevalent solution is mechanical storage and encompasses pumped hydroelectric storage (PHS), compressed air energy storage (CAES) and flywheels. Thermal energy systems (TES) such as hot water (sensible heat), molten salt and other phase change material (latent heat) comprise another solution to storage. Electrochemical storage is represented by rechargeable batteries as well as flow batteries, while pure electrical storage may be employed by supercapacitors and superconducting magnetic energy storage (SMES). The last major category is chemical technologies such as hydrogen fuel cells and solar fuels.

Kinetic Energy			Potential Energy		
Thermal	Electrical	Mechanical		Electrochemical	Chemical
Hot Water	Supercapacitors	Flywheels	Pumped Hydro	Rechargeable Batteries	Hydrogen
Molten Salt	Superconductors		Compressed Air	Flow Batteries	Solar Fuels
Other Phase Change					

Figure 2.9 Energy storage technologies (after IEC, 2011).

Applying these various engineering solutions to the ESS sector depends largely on their power rating, how quickly they can respond and how long they can support the network for. Luo *et al.* (2014) provide an excellent summary of all the applications for ESS, but they also categorise these into three broad categories. The first is in maintaining power quality where a very fast response time is required, within milliseconds, and power ratings typically less than a MW. This would encompass voltage and frequency regulation, emergency back-up and stabilisation of network fluctuations. Flywheels, batteries, SMES and supercapacitors are most suitable for this role due to their almost instantaneous response time (Luo *et al.*, 2014).

In the category of bridging power, moderate response times (up to about 1 s) and power ratings (100kW–10 MW) are necessary to support the grid for up to a few hours at a time. This may be in the form of renewable integration, black start support, transmission and distribution stabilization and standing reserves. Batteries are most effective for this application, but fuel cells, flywheels and supercapacitors may also play a role here in the future (Luo *et al.*, 2014).

Energy management is the third and last category, which they subdivide based on power ratings into small/medium-scale (~1–100 MW) and large-scale (>100 MW). Here, response times are usually about a minute and can support the network for several hours to a matter of days. Typically, small to medium-scale systems provide the ability to time shift, peak shave and load level and allows for extra peak load capacity, thus deferring the need to upgrade transmission infrastructure. Again, batteries are the most effective solution here but fuel cells and solar fuels may offer promise, although still largely under development (Luo *et al.*, 2014).

Large-scale energy management may also act in same roles as small/medium-scale storage when required but they are normally designed with seasonal storage in mind (Luo *et al.*, 2014). Due to its simplicity and efficiency, PHS has dominated large-scale energy management for well over a century. Water is stored in two vertically separated bodies with a turbine and water pump between them. When electricity is not required, it is used to drive water upslope so that it can be used to generate energy at a later stage by directing the water downwards through a turbine (World Energy Council, 2016). As Luo *et al.* (2014) detail, existing projects are capable of storing in excess of 3 GW and last for well over 40 years, but require massive capital investment, long lead times and certain geographical conditions.

Also operating in this high capacity, low-frequency space is CAES and TES systems. A single CAES plant may provide over 100 MW by pressurising air into either underground or over-ground storage with excess electricity powering compressors. This can be discharged at a later stage to power electricity-generating turbines. TES systems may either store up to a few hundred MW as sensible heat, that is gradually heating a substance to store energy, or by latent heat, where a phase change allows for much greater energy storage such as in molten salt plants. This process results in low efficiencies, around 30 to 60%, and very slow response times, but it is not geographically limited, offers good energy density and requires relatively little capital input (Luo *et al.*, 2014).

The IEC (2011) estimated that approximately 129 GW of storage capacity was installed globally in 2010, with PHS accounting for almost 99% of that total. CAES was in a distant second place, capable of storing only 440 MW. This figure appears to be growing rapidly though. The IEA (2017c) reported that the global installed capacity for 2015 was 165 GW, and an online database of all installations verifies this by indicating that a total capacity of 171 GW was available in August 2016 (US Department of Energy, 2016). These recent appraisals show how the landscape is quickly changing, however.

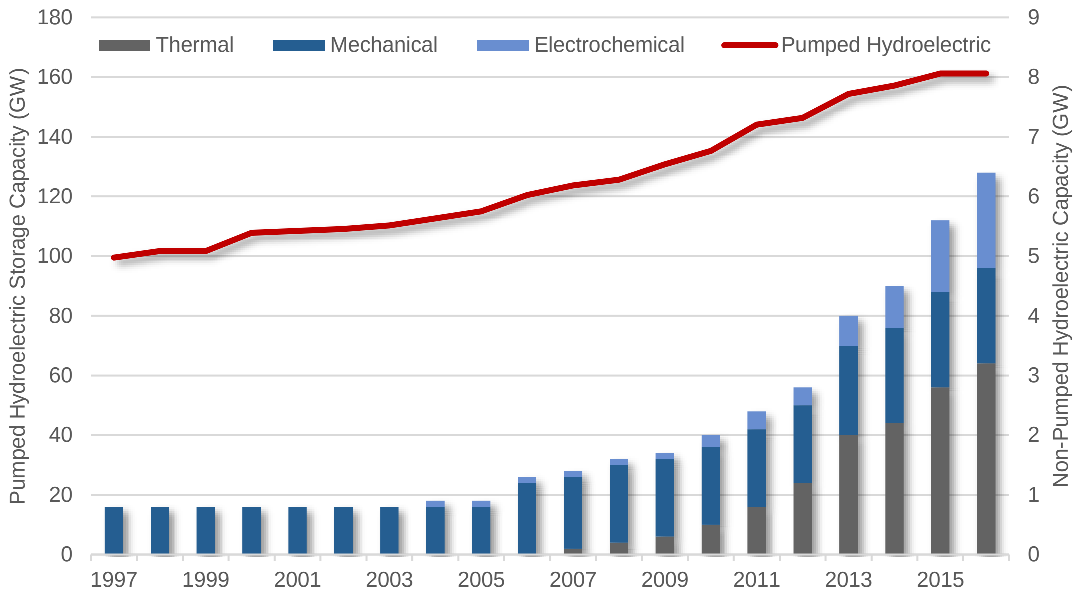

Figure 2.10 Global operational energy storage capacity between 1997 and 2016 according to the US Department of Energy (2016).

As observed in Figure 2.10, amongst non-PHS storage installations, thermal storage has taken the lead with around half of the existing capacity. The World Energy Council (2016) attributes this to the large scale of these projects. Two other solutions have a roughly equal share of the remainder of the non-PHS market, mechanical storage in the form of CAES and flywheels, and various forms of electrochemical storage. Interestingly though, electrochemical ESSs have grown at an average rate of 44% per annum compared to 3% growth for all mechanical storage installations, including PHS (US Department of Energy, 2016).

This is very significant for battery demand as flywheels are most effective in the applications of power quality, although still competing with batteries, and PHS, CAES and TES operate almost solely in the large-scale energy management domain. This makes batteries the most important and prevalent technology in the bridging power and small to medium-scale energy management categories, while also being able to provide support for power quality (Luo *et al.*, 2014; US Department of Energy, 2016). Of all the battery technology currently available, Li-ion batteries represent the highest energy density and efficiency while requiring no maintenance and offering a greater tolerance to operating temperatures (Diouf and Pode, 2015).

The IEA (2017b) provides details on non-PHS and non-TES installations and they indicate that Li-ion technology has dominated additions to capacity since 2013, growing to an estimated 90% for 2016. Previously lead-acid batteries were the most prevalent battery technology in ESS because of Li-ion's prohibitively high cost, but they now represent the third most used technology after PHS and TES systems at 1400 MW in 2016 (IEA, 2017b). Diouf and Pode (2015) predicted this trend, noting that the rise of their use in electric vehicles was driving remarkable amounts of research and investment. This has more than halved their cost since 2010 and made them more durable, making the lithium battery an attractive option for grid storage (Hocking *et al.*, 2016). In fact, it is suggested by some analysts to become a bigger market than EVs (Moncrief, 2010; Dunn *et al.*, 2011).

The three largest installations of Li-ion storage have been commissioned since 2016 in Australia, Germany and Japan, according to the US Department of Energy (2016) database. The largest of these in Jamestown, South Australia, has a capacity of 100 MW and was built within 100 days by Tesla and Neoen. All three of these projects highlight why Li-ion batteries are seeing a growing relevance. They were all designed to support renewable energy sources in frequency regulation and energy management (US Department of Energy, 2016).

Global electricity production grew to 24 660 TWh in 2016 with coal-fired power generation still responsible for the vast majority, around 40% (Figure 2.11) (IEA, 2017b; Enerdata, 2018). The contribution of renewable power generation is rising rapidly though, from 19.9% in 2010 to 24.4% in 2016, revealing the decline of fossil fuels. Hydroelectric power represents most of this generation but wind and solar power account for most of the growth, gaining 3.6% share of the world's electricity production (Enerdata, 2018). The IEA (2017b) revealed that net additions to renewable energy capacity in 2015 were 153 GW, 15% growth over the previous year, accounting for more than half of new installations for the first time. This is almost double the additions to coal generation, 84 GW, for the same period.

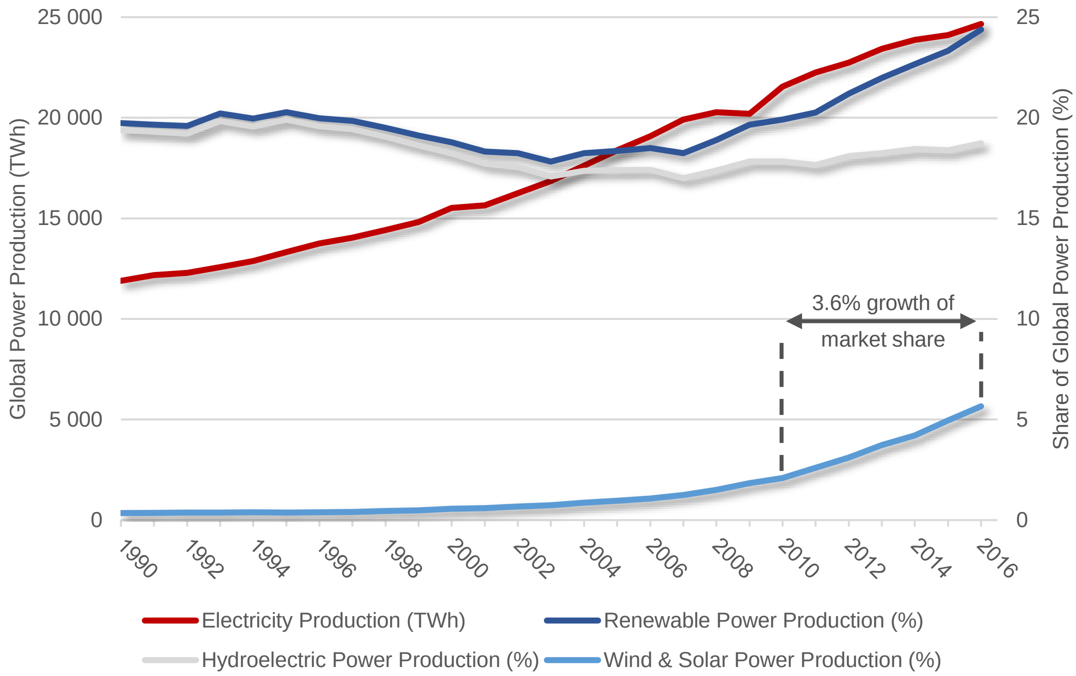

Figure 2.11 Annual global electricity production and the share of renewable generation, derived from Enerdata (2018).

Batteries are required to integrate intermittent power sources such as wind and solar generation so that electricity production may be decoupled from demand. Li-ion is technology is proving to be the most popular technology for this purpose, aided by improvements gained in its adoption in the electric vehicle sector (Diouf and Pode, 2015; World Energy Council, 2016; IEA, 2017b). The growth of the EV sector may also assist in the future requirements for ESS capacity, as the World Energy Council (2016) and Diouf and Pode (2015) indicate. As the number and age of EVs grow, second-use batteries will become more available at a significantly lower cost for stationary energy storage applications. ESS does not require the same energy efficiencies as vehicles and their batteries may be re-purposed once they are not effective enough for EVs.

Vehicle-to-grid technology may form another link between these sectors, where EV batteries may be charged during off-peak periods and sold off during peak hours. The integration of EV into the grid is receiving a lot of attention and research at present and is already being demonstrated in Denmark, the UK and the US (Mwasilu, Justo, Kim, Do and Jung 2014; Habib, Hamelin and Wenzel, 2016; Tan, Ramachandaramurthy and Yong, 2016).

2.6 Market Drivers

The world's rapidly growing population consumed an estimated 13 903 million tonnes of oil equivalent (Mtoe) to power their every need in 2016, about 1.87 toe per capita every year. This equates to nearly 162 000 TWh and is still not sufficient to provide basic access to electricity for around 1.2 billion people (IEA, 2017b; Enerdata, 2018). Energy requirements are still rising rapidly and are expected to reach 244 000 TWh, or 21 000 Mtoe, by the year 2050 (World Energy Council, 2013).

The IEA (2017b) reports that there is a growing awareness of our environmental impact as we experience climate change and the health consequences of pollution. For instance, air pollution linked to energy generation is still responsible for 6.5 million deaths per year. This is one of the main drivers behind a significant shift seen in the energy industry, in addition to alleviating issues such as energy poverty and security. The need to meet future energy requirements must be done without increasing global carbon dioxide emissions and other greenhouse gases, which have been established to be responsible for the trend in global warming (Cox, Betts, Jones, Spall and Totterdell , 2000; Larcher and Tarascon, 2015).

The simplest manner to illustrate this shift in energy consumption is by observing global carbon dioxide emissions. While it may still be too early to prove empirical, Figure 2.12 shows that total carbon dioxide emissions have roughly stabilized since 2014 and were around 31.5 $GtCO_2$ in 2016. Additionally, global carbon dioxide intensity (per capita) has been slowly decreasing since 2013 to levels of around 4.23 tCO_2 per capita in 2016 (World Bank, 2017; Enerdata, 2018). The manner in which global energy is derived is responsible for these emissions, with coal, oil and gas accounting for 81.4% of all energy generation and 99.4% of all CO_2 emissions in 2015. The sectors most at fault for these emissions are electricity and heating generation (42%) and transport (24%), making up around two-thirds of the world total (2015) (IEA, 2017a, 2017d).

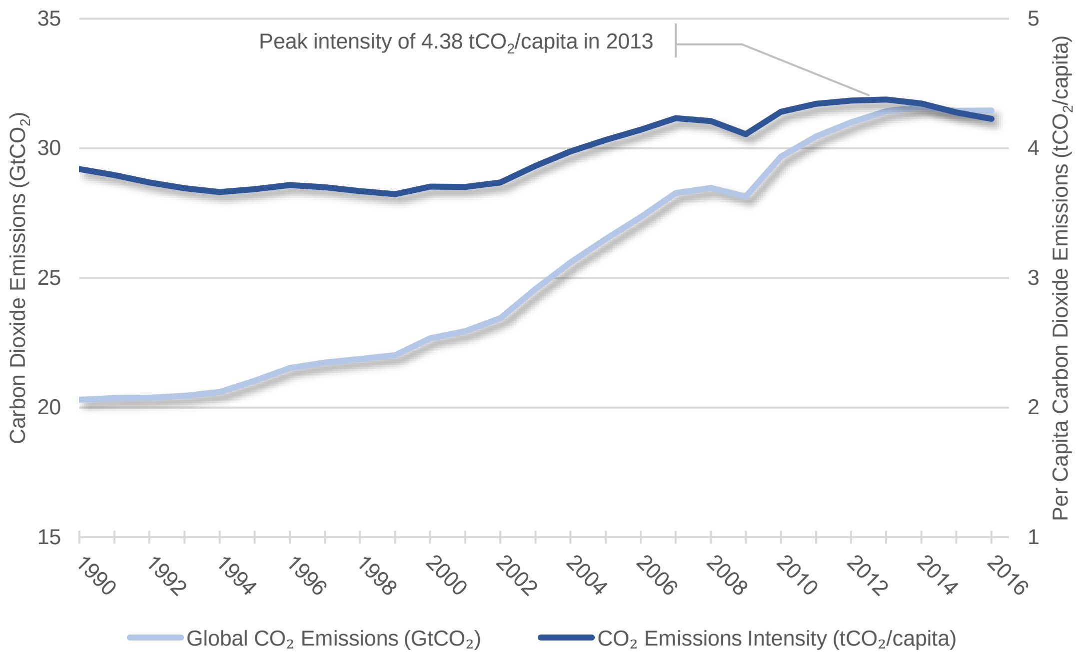

Figure 2.12 Global carbon dioxide emissions and per capita intensity between 1990 and 2016 (derived from Enerdata, 2018; World Bank, 2017).

The key to providing for our increasing energy demands while reducing emissions, as suggested by Larcher and Tarascon (2015), is placing technological innovation as a global imperative. They go on to detail that even if the transport sector is transformed by the widespread adoption of electric vehicles, this alone will not reduce emissions, and may even increase them in the worst-case scenario. When accounting for CO_2 produced in electric vehicle manufacturing, supplied with electricity from completely coal-derived generation, ICE vehicles produce significantly less CO_2 over their lifetime. Thus, the emphasis for transformation must also be placed on the power generation sector. Several renewable energy sources are available, such as wind, solar, tidal, biomass and geothermal, but they necessitate energy storage systems in order to integrate their intermittent nature (Larcher and Tarascon, 2015).

The Intergovernmental Panel on Climate Change (IPCC) tracks how emissions have already impacted our environment since pre-industrial times, defined as roughly the middle of the 19th century. In their Fifth Assessment Report, they indicate that globally averaged surface temperatures have risen by 0.85 ˚C, global mean sea level rose by 0.19 m and surface ocean water became 26% more acidic. Most of this is “extremely likely” to have been caused by human influence (IPCC, 2014). An alarm was raised by the economist William Nordhaus (1977) who stated that a rise in temperatures over 2 ˚C would be unprecedented in temperature patterns in the last 100 000 years.

Adopting Nordhaus’ benchmark, the United Nations Framework Convention on Climate Change (UNFCCC) is the most significant international environmental treaty. Formulated in 1992, the latest accord is the Paris Agreement, which requires all ratified countries to take action in keeping global temperatures well below the 2 ˚C above pre-industrial levels and pursue efforts to limit temperature increases to 1.5 ˚C (UNFCCC, 2014). The agreement was ratified in 2016 aided by the signatures of both the US and China, the most polluting countries, and since then 173 nations have committed to the convention. This requires all signed parties to submit and publish nationally determined contributions (NDCs) to the United Nations in an effort to reduce their emissions (UNFCCC, 2014).

To put these aims into perspective, the IEA (2017b) has created three scenarios leading up to the year 2100 (Figure 2.13). The Reference Technology Scenario (RTS) considers all current commitments by nations to limit emissions and improve efficiencies. This would result in a 2.7 ˚C average increase by 2100 with cumulative emissions of 1 750 $GtCO_2$. The Two Degree Scenario (2DS) models a 50% chance of limiting temperature rise to 2 ˚C by 2100 and cumulative emissions of 1 170 $GtCO_2$, representing a major transformation of the energy sector. The Beyond Two Degree Scenario (B2DS) allows for only 750 $GtCO_2$ of cumulative emissions by 2060 and will likely result in a 1.75 ˚C rise. This, however, is a long way from the reality of today's energy sector and represents the highest aspirations of the UNFCCC (IEA, 2017b).

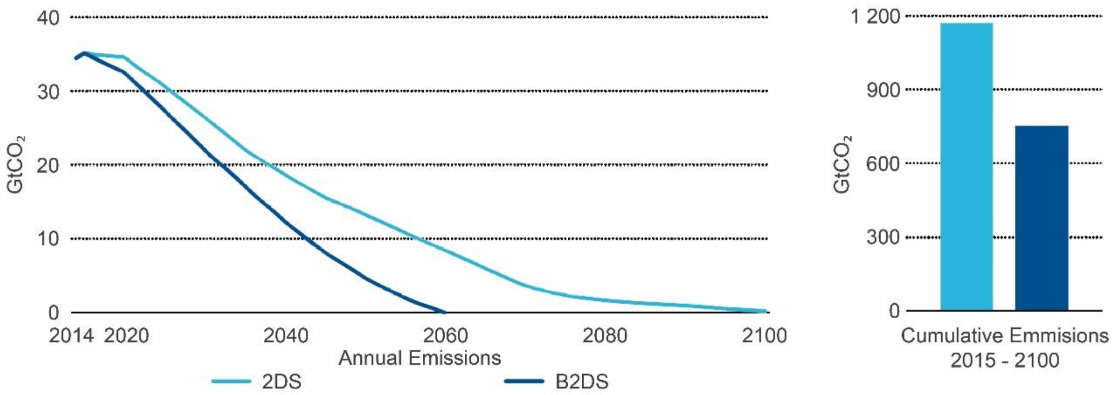

Figure 2.13 Annual and cumulative emissions modelled in the Two Degree and Beyond Two Degree Scenarios (IEA, 2017b).

Amongst the varied goals of the NDCs, there is a consensus that states will strive to halt the growth of emissions, drastically reduce the carbon intensity of their GDP as well as improve their non-fossil fuel supply of energy (UNFCCC, 2014). Countries that are part of this agreement are actively encouraging the development of renewable energy, energy storage and electric vehicles through a diverse array of policy implementations. For instance, budgets for investment in clean energy research are set aside to further their development. Financial incentives such as subsidies, tax waivers and rebates are commonplace over and above tariffs placed on fossil fuel power consumption and conventional ICE vehicles. Non-financial incentives include access to parking and inner-city areas for electric vehicles (IEA, 2017b, 2017c).

In solar and wind installations specifically, auctions for projects are growing in popularity and have resulted in levels of competition that provide renewable power cheaper than that of fossil-fuel generation (REN21, 2017). Depicted in Figure 2.14, prices of solar photovoltaic installations around the world are falling rapidly (IRENA, 2017b). The greatest contributor to emissions, China, is the leading country in renewable energy installations at 40% of capacity growth and by far the largest electric car market at 336 thousand new additions in 2016 (IEA, 2017c, 2017e). There is also an increasing number of countries that have called for the end of ICE vehicle sales. Britain and France announced intentions for this to occur by 2040 and Norway by 2025 with many more, such as China, Germany and India, considering similar targets (Petroff, 2017).

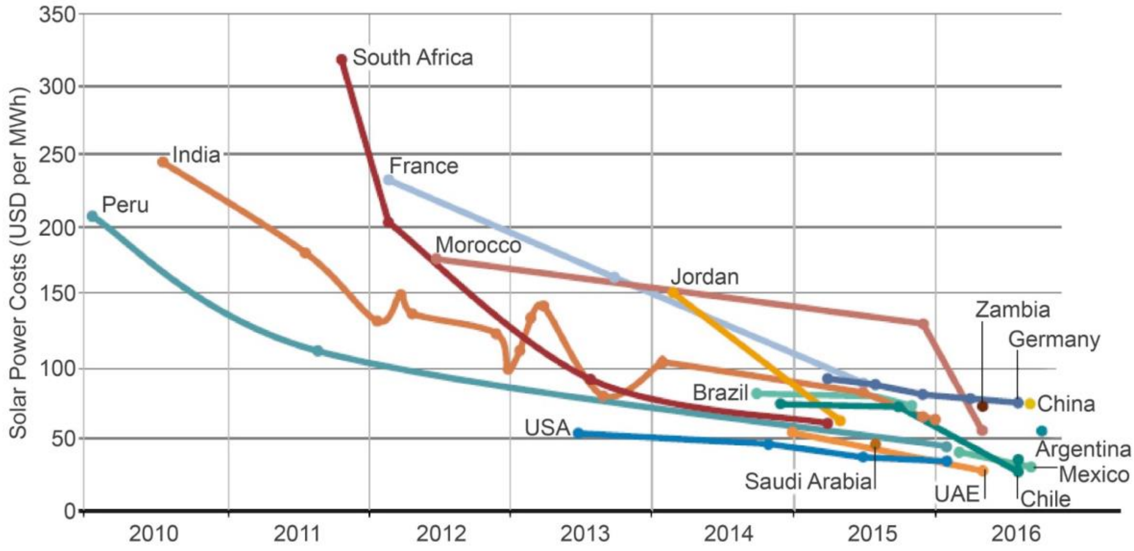

Figure 2.14 Auction prices for utility-scale solar photovoltaics between 2010 and 2016 (IRENA, 2017b).

Of all the clean energy technology available, only three sectors are on track to limiting temperature increases to 2 ˚C by 2100. These sectors are solar photovoltaics and onshore wind generation, electric vehicles and energy storage. The IEA (2017b) ascribes this to increased cost competitiveness and improved performance through research in addition to the incentives provided by governmental policy. The most dominant technology behind all these sectors is the Li-ion battery, which is why it has seen a massive surge in demand. The IEA (2017b) warns, however, that to keep these sectors on target, raw material supplies are becoming increasingly critical to ensure that these costs can be maintained. Therefore, decreasing material requirements and increasing energy density are necessary for supporting the widespread adoption of Li-ion batteries in electric vehicles and grid storage.

There are many detractors of the Paris Agreement, but one of the most publicized is an article in Nature (Rogelj, Elzen, Den, Fransen, Fekete, Winkler, Schaeffer, Sha, Riahi and Meinshausen, 2016). The authors pointed out that the vagueness of individual NDCs is a serious fault. Specifically, when the goals are modelled, they only result in a 2.4 $GtCO_2$ reduction in annual emissions by 2030, far short of the required 9 $GtCO_2$. Many sectors and countries are also neglected in the agreement such as the commitment from the aviation and maritime transport industry. Regarding each country's NDC, reference baselines are often omitted in mentioning targets and many do not state goals in relation to the emission intensity of their GDP for example. In the worst cases, targets are qualitative and thus signatories will not be able to be held accountable to a large degree. On top of this, each nation is responsible for accounting for their own historical emissions by different analysts leading to even further ambiguity (Rogelj *et al.*, 2016).

Nickless (2017) highlights one of the greatest shortfalls of this agreement, considering that this move towards a less carbon-intensive global economy will drive additional demand for metals and minerals. There is no account of where these metal supplies will come from in the future. Furthermore, as mining grades decrease over time, production will become more expensive, require greater energy and water inputs and result in increased waste and emissions. Therefore, while this has the potential to reduce the global environmental footprint, he calls for a unified action on mineral production and monitoring of its impacts. This would hopefully mitigate any future mineral crises that could result from the disassociation between consumers and where their metals originate (Nickless, 2017).

Nevertheless, the UNFCCC and its Paris Agreement is the most significant environmental accord to date due to its widespread acceptance and already appears to be making an impact. There are vast array of other conventions and agreements in place on a global down to a city scale, such as the Geneva Convention on air pollution (UNECE, 1979) or the Cities and Climate Change Initiative (OECD, 2014), but they all point to a necessary shift in the energy sector that may be enabled by Li-ion battery technology.

2.7 Competing Technologies

The technological requirements of the EV sector compared to ESS for grid storage is markedly different. Within the vehicle industry, manufacturers' primary concern is energy to weight and volume ratio while also requiring very high energy cycling efficiencies. This can provide further vehicle ranges that users are accustomed to in ICE vehicles (Diouf and Pode, 2015; Hocking *et al.*, 2016). In stationary energy storage, energy capacity and self-discharge are major factors in deciding on a suitable technology, with less emphasis placed on cost, weight and volume. Furthermore, from the perspective of national regulators, maturity, reliability and possible environmental impacts are all important characteristics viewed in their evaluation (Luo *et al.*, 2014). Considering this, alternative technologies competing against Li-ion batteries are evaluated within this section.

2.7.1 The Electric Vehicle Sector

Literature focussed on battery technologies used in the EV sector often cite four main competitors as seen in Table 2.4; lead-acid, NiCd, NiMH and Li-ion. Lead-acid has traditionally dominated the vehicle sector and still does, due to its reliability and the smaller power demand from ICE vehicles. However, it has very low cycle life, specific energy density and is very environmentally toxic, which does not make it suitable for EVs (Macquarie Research, 2016).

Table 2.4 Comparison of secondary battery technologies for the EV sector.

Properties	Lead Acid	NiCd	NiMH	Li-ion
Specific Energy (Wh/kg)	30 - 50	45 - 80	60 -120	90 - 250
Cycle Life	200 - 300	1000	300 - 500	500 - 2000
Self-discharge per Month	5%	20%	30%	3 - 5%
Voltage (nominal)	2 V	1.2 V	1.2 V	3.3 - 3.8 V
Maintenance	3 - 6 months	1 - 2 months	2 - 3 months	Not required
Safety Requirements	Thermally stable.	Thermally stable. Fuse protection common.		Protection circuits mandatory.
Toxicity	Very high	Very high	Low	Low
In Use Since	Late 1800's	1950	1990	1991

Source: (Panasonic, 2011, 2012b, 2012a, 2012c; Lu, Han, Li, Hua and Ouyang, 2013; Diouf and Pode, 2015)

NiCd batteries share this toxicity due to the heavy metals required for its electrodes but also exhibits much higher self-discharge rates despite possessing significantly better cycling life. NiMH technology is not environmentally toxic and offers specific densities up to 120 Wh/kg, which is why it has been applied in many hybrid vehicles. However, its cycle life is not significantly better than lead-acid and may self-discharge 30% of its energy every month. It is also only capable of supplying a nominal voltage of around 1.2 V (Diouf and Pode, 2015; Manzetti and Mariasiu, 2015).

While lithium batteries remain more expensive than lead-acid, NiCd and NiMH electrochemical storage, their comparably higher energy density is the most critical factor in the adoption of new plug-in varieties of EVs. Li-ion technology is considered to be unrivalled in this respect, providing the furthest vehicle ranges in the smallest battery form, evident in their rapidly growing market segment (Diouf and Pode, 2015; Hocking *et al.*, 2016). Gruber *et al.* (2011) expect that lithium batteries will dominate all implementations in EVs, although NiMH currently represents the market leader in hybrid (non-plug-in) varieties (Macquarie Research, 2016).

The substitution of Li-ion batteries by new technologies is always difficult to forecast but the literature reviews several possibilities. Although sodium batteries have received much attention as a plausible competitor, Larcher and Tarascon (2015) indicate that it cannot theoretically improve on lithium's gravimetric and volumetric capacities. Aluminium-air technology has been shown to have much higher energy densities than Li-ion, but its development is still in its infancy (Larcher and Tarascon, 2015; Hocking *et al.*, 2016). Hydrogen fuel cells were once seen as a viable option in vehicles due to its low emissions, but it is up to five times more expensive than fossil fuels beyond the fact that it requires an intensive infrastructural network (Hocking *et al.*, 2016; The Economist, 2017).

2.7.2 The Energy Storage Sector

Two papers by Zakeri and Syri (2015) and Luo *et al.* (2014) provide a comprehensive review of the various technologies available to the grid-scale energy storage sector. Both sources divide the multitude of ESS applications into three types; long-duration and frequent usage, medium-duration and fast response, and short-duration and highly frequent usage. Li-ion batteries are most relevant in the medium-duration category, although they may also be applicable in either of the other two domains. For this reason, an analysis of competing technologies will be limited to those that may be pragmatic in the medium-duration class, which covers both bridging power and small to medium-scale energy management (Luo *et al.*, 2014; Zakeri and Syri, 2015).

Table 2.5 Comparison of ESS technologies available for medium-duration and fast response.

Technology	Energy Density[1]	Specific Energy[2]	Existing Power Rating[3]	Self-discharge[2]	Lifetime[1]	Efficiency[1]	Discharge Duration[1]	Average Capital Energy Cost[2]
Units	*Wh/l*	*Wh/kg*	*MW*	*% Daily*	*Years*	*%*		*USD/kWh*
Li-ion	200-500	150-350	<100	0.1-0.3	5-15	90-97	min - hrs	672
Lead-acid	50-80	30-50	<10	0.1-0.3	5-15	70-80	sec - hrs	538
NaS	150-250	150-250	<50	20	10-15	75-90	sec - hrs	422
$NaNiCl_2$	150	100-140	<5	15	15	86-88	hrs	1347
NiCd	60-150	15-300	<27	0.2-0.6	10-20	60-70	sec - hrs	860
VRB	16-33	10-35	<15	small	5-10	75-85	sec - days	378
ZnBr	30-60	30-85	<1	small	5-10	65-75	sec - hrs	271
PSB	20-30	15-30	-	small	10-15	60-75	sec - hrs	1411
Hydrogen Fuel Cells	500-3000	100-10000	<6	negligible	5-15	20-50	sec - days	664
Flywheel	20-80	5-100	<400	100	15	90-93	sec - min	5893
Overground CAES	-	-	<2	small	20-40	75-90	sec - min	113

Sources: Luo *et al.* (2014)[1], Zakeri and Syri (2015)[2] and the US Department of Energy (2016)[3]

It is clear from the abundance of competing technologies seen in Table 2.5 that the dominance of Li-ion is far from as secure as it is in the EV space. This due to the reason that high cycling efficiency and energy density are less prized over practical power capacity and self-discharge. Nevertheless, these characteristics are important in localised storage where space is at a premium (Luo *et al.*, 2014). The potential of Li-ion lies in its ability to cover a wide range of capacity requirements, up to 100 MW, while being able to respond within milliseconds and exhibiting very low self-discharge rates. It also requires very little to no maintenance over its moderately long lifetime, which is rare amongst its competitors (Zakeri and Syri, 2015; US Department of Energy, 2016).

Safety and cost competitiveness is often cited as the greatest inhibitors to its adoption. Hocking *et al.* (2016) address this, stating that safety is improving through the use of battery management systems and ongoing research. They also go on to report that while Li-ion ESS costs were around 1000 USD/kWh, they halved in the five years preceding 2016 and are set to fall even further. Recently, the largest Li-ion installation, commissioned at the end of last year in Australia, was constructed at a cost of only 250 USD/kWh (US Department of Energy, 2016).

Looking at its competitors in electrochemical storage, lead-acid batteries have a strong track record in safety and reliability but exhibit significantly lower energy density and shorter discharge durations (Zakeri and Syri, 2015). They are viewed as a low-cost alternative, but their low cycle life means that need to be replaced more often, especially if they operate outside of their narrow temperature range (-5 to 40 ˚C) (Brown and Chvala, 2003). Advanced valve-regulated lead-acid batteries allow for up to a ten-fold improvement in lifetime, but these are roughly 30% more expensive (Schoenung and Eyer, 2008; Poullikkas, 2013).

Sodium-sulphur batteries have seen success in inexpensive large-scale installations of up to 50 MW due to their relatively high efficiencies and moderately long lifetime and discharge duration (7 h) (Díaz-González, Sumper, Gomis-Bellmunt and Villafáfila-Robles, 2012). Similar in chemistry, sodium-nickel-chloride batteries, also known as ZEBRA batteries, achieve higher efficiencies and require no maintenance, unlike NaS, but are significantly more expensive. The disadvantage of both these technologies is that they require high operating temperatures which consumes their own energy leading to 15 to 20% "self-discharge" on a daily basis (Luo *et al.*, 2014).

In contrast, NiCd batteries have seen very few successes as it displays short discharge durations and moderate efficiencies. Furthermore, its components are environmentally toxic, it is relatively expensive and suffers from the memory effect – where partial charging and discharging can reduce capacity (Zakeri and Syri, 2015). Only two operations exist and it seems unlikely that it will be pursued further (Luo *et al.*, 2014; US Department of Energy, 2016)

Flow batteries differ from conventional batteries in that they store energy in the reduction and oxidation of the electrolyte solution instead of the electrodes. Electrolytes are carried away from the cell after charging into storage tanks for later discharging (Luo *et al.*, 2014). Existing flow battery technologies, vanadium redox (VRB), zinc bromine (ZnBr) and polysulphide bromine (PSB) all exhibit very similar characteristics. They have low energy density and specific energy, moderate efficiencies and lifetimes, however, their self-discharge is small, they can support the grid for days at a time and they are one of the cheapest technologies available (Zakeri and Syri, 2015). The exception is PSB, which is evident to be costly and unproven, although VRB and ZnBr have installations of up to 15 MW globally (Luo *et al.*, 2014; US Department of Energy, 2016). Flow batteries may prove to be the strongest electrochemical competitor at large-scales and over long discharge periods, especially in medium to large-scale energy management (Zakeri and Syri, 2015).

Hydrogen storage has received a lot of attention due to its very high energy density and specific energy that can be stored indefinitely with negligible loss. It also emits only water vapour when converted into energy and is easily scalable to hundreds of MW (Luo *et al.*, 2014). There are complications in its economics, however. It requires a large energy network of storage tanks and pipelines, similar to petroleum, and achieves very low energy efficiencies, from 20 to 50%. This may be a promising technology but requires further development and research (Larcher and Tarascon, 2015; Zakeri and Syri, 2015).

Only two mechanical storage technologies compete in this moderate-duration domain. Flywheels store energy by accelerating and discharge this via an integrated motor/generator to supply high power ratings for short durations, typically up to an hour. Magnetic bearings and low vacuum environments may make these extremely efficient, but they still lose around 20% of their energy every hour when idling (Díaz-González *et al.*, 2012; Luo *et al.*, 2014). Thus, they are most often employed in frequency regulation or as a spinning power reserve but are being studied for use in energy management (IEC, 2011; Enerdata, 2018). Overground or modular small CAES exhibits the slowest response time of all these technologies but it may be most relevant in small to medium-scale energy management. Although it has a relatively low energy density, it has high energy efficiencies, a long lifetime and by far the lowest capital costs (Zakeri and Syri, 2015). Yet, very few operating installations exist at present and only at power ratings of less than 2 MW (Enerdata, 2018).

In summary, many technologies exist in this range of applications and each exhibit unique advantages and disadvantages, which will be valued on a project by project basis. While Li-ion appears to be the most suitable for most applications due to its characteristics as long its costs continue to decline, the market will ultimately decide on which will be the most pragmatic. As the IEA (2017b) indicates though, lithium rechargeable batteries seem to be taking the major share of new installations.

2.8 Efficiencies and Intensity of Use

As Roberts (1992) indicates, the material composition of product is critical in determining the consumption of any particular market. With regards to lithium, this may be stated as the amount of lithium required to produce a unit of power sustained over a certain period, such as grams LCE per kWh. The product composition of output must also be determined with relevance to the EV and ESS sectors. The typical energy requirements for EVs, or battery sizes, must be analysed before being placed into perspective with annual global sales in order to determine the lithium demand for the industry. In the same manner, the lithium needs of ESS may be estimated by quantifying the cumulative energy ratings of new installations annually and multiplying it by the lithium composition of each unit of energy.

The potential size of each sector, or output, cannot be viewed without considering the intensity of product. For example, there are many more mobile phones than vehicles, but their individual lithium requirement is less than 3 grams LCE. EVs however, may require over 20 kg LCE per unit depending on their rated power (Evans, 2014). The higher capacity requirements of both EV and ESS sectors mean that they have a greater potential than any other Li-ion battery application in terms of lithium consumption (Hocking *et al.*, 2016).

Roberts (1992) also describes that technologies follow what he terms as a learning curve. As energy output increases, the amount of material required to produce the same amount of product decreases over time, thus lowering the material composition of product. This is a well-established phenomenon and can be illustrated by the amount of aluminium required to produce a single beer can over time, for example. In 1964, around 25 g was required to produce a single can, falling to 17 g in 1985 due to various efficiencies in the manufacturing procedure (Roberts, 1992).

Rechargeable lithium batteries are not an exception to this trend and can be seen in the rapid improvements in both specific energy density (Wh/kg) and lithium required per kWh. The earliest iteration of Li-ion batteries, LCO, had an energy density of only 80 Wh/kg and were designed to power portable electronics (Nishi, 2001). Today, the latest state-of-the-art technology is the NCA cathode that is reported to produce 243 Wh for every kilogram (Panasonic, 2012b; Nitta *et al.*, 2015). These NCA batteries are currently produced by Panasonic and are used to power modern EVs built by Tesla (Nitta *et al.*, 2015). While the lithium requirements of each of these technologies are similar, the improved energy of new chemistries translates into less lithium required per kWh (Macquarie Research, 2016).

This supports the claim by Scrosati and Garche (2010), indicating that marginal increases have been made by optimizing cell design and manufacturing processes, but true breakthroughs in performance rely on innovative chemistries. They detail that the evolution of chemistry has been driven by the race to improve lithium battery performance and safety for its application in the EV industry. The focus of these advances has typically involved cathodic chemistry and structure while graphite or carbon has remained the dominant anode (Nitta *et al.*, 2015). Innovation in the chemistry of Li-ion battery anodes and electrolytes is suggested as possessing the greatest potential for improvement (Scrosati and Garche, 2010; Hocking *et al.*, 2016).

Providing an estimate of lithium consumption in batteries is difficult due to the variety of chemistries in production as well its designed application. LCO batteries, which are particularly suited to mobile electronics, require around 7% lithium by weight, whereas LFP batteries, commonly used in electric bikes, requires only around 4% by weight (Macquarie Research, 2016). Moreover, producers consider these chemistries as their intellectual property and are careful not to provide details on their makeup (Hocking *et al.*, 2016). Nevertheless, various independent studies have been undertaken in addition to analysts providing their own estimates of lithium consumption.

Tahil (2010) suggested that 320 g of Li was required for each kWh, while Kushnir and Sandén (2012) published a figure of 200 g/kWh, with a reasonable expectation of 160 g/kWh in the near future. On the lower side, Gruber *et al.* (2011) estimated that only 114 g Li was required for each kWh. Speirs, Contestabile, Houari and Gross (2014) provide a likely range of intensity determined from a thorough literature review, from 190 to 380 g/kWh, to cover all possible scenarios. Industry analysts, however, seem to agree that lithium consumption was around 120 to 190 g/kWh in 2016 and is still expected to decline slowly (Hocking *et al.*, 2016; Macquarie Research, 2016). This is already significantly less than the earliest estimates of intensity. It should be stated, though, that these calculations are based on the EV industry. The only datum found specific to ESS is marginally lower than these estimates at around 110 g Li/kW, or 600 kg per MW (Brown *et al.*, 2016).

Research has also drastically improved the life of this technology beyond 2000 cycles, from what was only 500 cycles previously, with the commercial production of LFP and NMC cathodes (Diouf and Pode, 2015; Nitta *et al.*, 2015). In effect, this allows longer periods without the need for replacement, thus requiring less lithium over the lifetime of the particular application. However, life cycle assessment studies still widely adopt a range of 5 to 15 years depending on the frequency of usage (Vikström, Davidsson and Höök, 2013; Luo *et al.*, 2014; Zakeri and Syri, 2015).

Increased cost-competitiveness of Li-ion batteries, seen in Figure 2.15 for EVs, does relate to improved efficiencies due to manufacturing procedures, economies of scale and performance-enhancing chemistries but it is not linked to lower lithium intensity of product (Macquarie Research, 2016; Olivetti, Ceder, Gaustad and Fu 2017). However, it is often argued to be critical to widespread adoption and thus, lower battery costs will result in a greater rate of lithium consumption at a global scale. Of course, the opposite will also be true if Li-ion batteries become too expensive for the market or a substitute is proven to be more pragmatic (Speirs *et al.*, 2014; Diouf and Pode, 2015; Oliveira, Messagie, Rangaraju, Sanfelix, Hernandez Rivas and Van Mierlo, 2015).

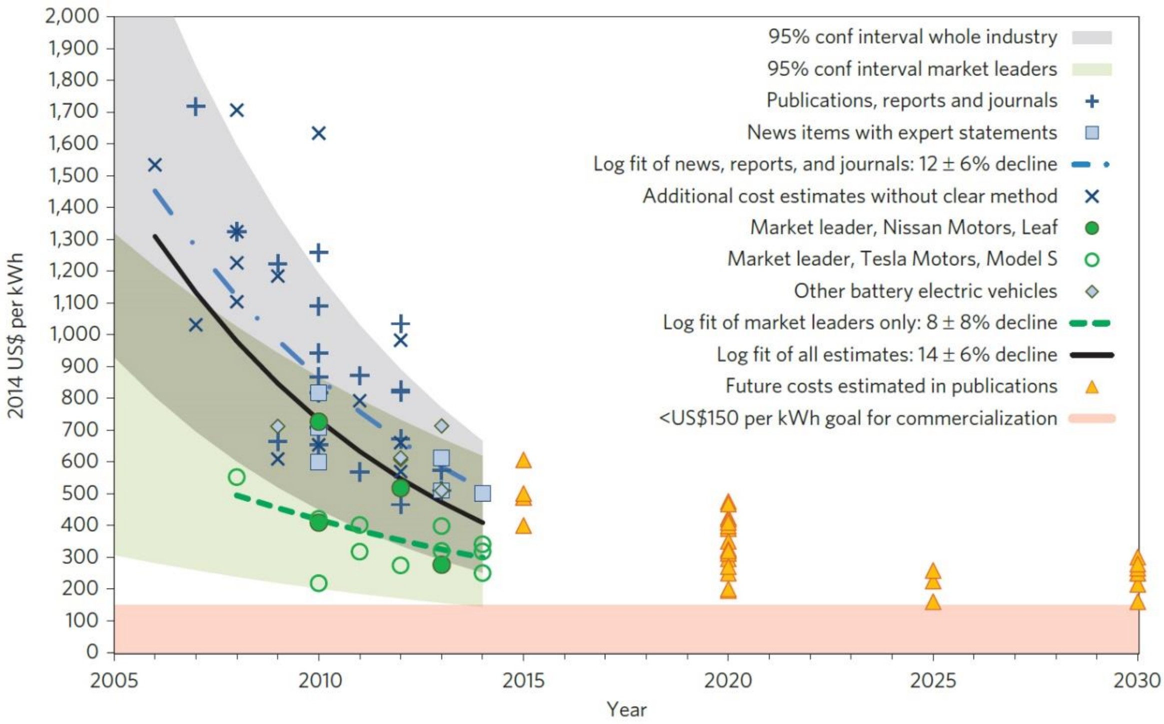

Figure 2.15 Historical and forecast costs of Li-ion batteries in the EV sector according to publications, announcements and manufacturing (Nykvist and Nilsson, 2015).

Drastic improvements in energy density could yet be found in research surrounding the anode in Li-ion batteries. Lithium batteries in their current form, such as LCO, have a maximum theoretical specific energy of around 380 Wh/kg. If sulphur or oxygen are used, though, as the positive electrode instead of traditional carbon-based forms, they display theoretical densities of 2500 to 3500 Wh/kg respectively (Bruce, Freunberger, Hardwick and Tarascon, 2011). Thus, they are seen as the holy grail of the automotive transport industry and have received colossal amounts of attention recently. These Li-S and Li-O_2 batteries are still in development, however, as they suffer from a lack of suitable electrolytes, but the progress looks promising (Larcher and Tarascon, 2015). While providing significantly greater energy densities, they also have the advantage of not relying on the supply of more scarce metals such as cobalt, nickel and copper (Bruce *et al.*, 2011). The danger, however, is that these may result in a larger Li-ion market share as well as increased battery capacities, leading to much greater lithium demand (Speirs *et al.*, 2014).

Estimates of lithium intensity per kWh provide an effective basis for forecasting future lithium requirements when linked with various projections of ESS and EV markets. This may be compared to future availability of lithium supplies to establish if there are any possible shortfalls, which has a consequence on relevant metal prices.

3 AVAILABILITY OF LITHIUM

Scarcity or availability of mineral resources is often solely viewed in terms of geological abundance, but Henckens *et al.* (2016) elaborate that this geological scarcity must be distinguished from economic scarcity. The latter takes into account various geopolitical actions, such as changes in policy, strikes and boycotts, the effects of a producer-controlled market, as well as changes in demand, which will be considered in section 4. The literature is assessed in terms of pure structural abundance first, and then how producers play a role in this availability. Finally, the potential contribution from secondary sources via recycling is also evaluated.

3.1 Sources of Lithium

Primary production of lithium is derived from mining two major economic sources of lithium. Historically, the first type of deposit to be exploited at a commercial scale was mineral pegmatites. *Pegma* is a Greek word meaning “congealed” or “hardened”, which is apt in describing its derivation. Once a magma of granitic composition has intruded into earth’s crust and begins to cool, the most diffusive elements are enriched while the granite hardens. The remaining fluid containing rare-earth elements and alkaline metals, such as lithium, rubidium and caesium, is either trapped within the granite or escapes radially through fractures before cooling and hardening. This creates pockets, veins or zones of enrichment where lithium occurs within silicates, alumino-silicates and phosphates (Grosjean, Miranda, Perrin and Poggi, 2012).

Due to its high reactivity, lithium occurs within a wide array of minerals, although only a few are known to possess lithium concentrations that are considered viable, shown in Table 3.1. Spodumene, the most economically important and abundant of these, containing 3.7% lithium by weight, commonly occurs alongside lepidolite (1.39-3.6% Li) and petalite (1.6-2.27% Li) in pegmatites. Eucryptite, amblygonite and zinnwaldite are also typical lithium-bearing minerals found in these deposits but occur in minor amounts. Grades at operating pegmatite mines typically fall within the range of 1.5 to 4% Li_2O, and 60 to 70% of the lithium is recovered (Brown *et al.*, 2016). Grosjean *et al.* (2012) indicate that the time for recovery is relatively short in the case of hard-rock minerals, taking around 5 days in total.

Table 3.1 Common Li-bearing minerals found in economic concentrations.

Name	Formula	Lithium Content (% Li)	Colour and Lustre
Spodumene	$LiAlSi_2O_6$	3.7	White, colourless, grey, pink, lilac, yellow or green; vitreous
Lepidolite	$K_2(Li,Al)_{5-6}\{Si_{6-7}Al_{2-1}O_{20}\}(OH,F)_4$	1.39 – 3.6	Colourless, grey/white pink, lilac, yellow or white; vitreous to pearly
Petalite	$LiAlSi_4O_{10}$	1.6 – 2.27	Colourless, grey, yellow or white; vitreous to pearly
Eucryptite	$LiAlSiO_4$	2.1 – 5.53	Brown, colourless; vitreous
Amblygonite	$LiAl[PO_4][F,OH]$	3.4 – 4.7	White, yellow or grey; vitreous to pearly
Zinnwaldite	$KLiFe^{2+}Al(AlSi_3)O_{10}(F,OH)_3$	1.59	Light brown, silvery-white, grey, yellowish to greenish white; pearly to vitreous
Hectorite	$Na_{0.3}(Mg,Li)_3Si_4O_{10}(OH)_2$	0.54	White, opaque; earthy
Jadarite	$LiNaSiB_3O_7(OH)$	7.3	White; porcellanous

Source: (Brown *et al.*, 2016)

The great variety of lithium mineral characteristics, such as composition, density and hardness results in difficulties in processing as each mineral requires a unique method to liberate it from the gangue. If a mineral is not present in sufficient concentrations, then it will too be treated as gangue and remain unrecovered. The nature of pegmatite occurrences as narrow veins and pockets lends itself to unpredictability and access difficulties (Grosjean *et al.*, 2012). Inevitably, its extraction causes environmental damage and the processing method requires roasting or calcining, which has an impact on air quality. Likewise, chemical effluent and wastewater may also be produced in the treatment of ore (Evans, 2014).

Other significant mineral occurrences of lithium are found as silicates in evaporates, which are deemed to result from solar evaporation and sedimentation in ancient geological basins. Hectorite is a soft white greasy clay derived from the hydrothermal alteration of volcaniclastic sediment in alkaline lakes that were heated by geothermal springs. Jadarite is a recently discovered, rare white chalky aggregate found in sedimentary sequences that is very highly concentrated in lithium (Grosjean *et al.*, 2012; Brown *et al.*, 2016). None of these alternative mineral deposits is currently in operation, however (Evans, 2014).

As the lightest metal and solid element at 20 ˚C, lithium floats on water and is concentrated in water subjected to high evaporation rates (Brown *et al.*, 2016). Continental brines represent the important lithium resource globally and form within endorheic or enclosed inland basins. Mineral salts are leached from surrounding volcanic rocks by ground and surface water, subsequent to weathering before they are carried into shallow basins. Here lithium is concentrated by evaporation along with other important elements such as boron and potassium, especially in regions of high altitude and low precipitation referred to as salars (Ide and Kunasz, 1989; Kesler, Gruber, Medina, Keoleian, Everson and Wallington, 2012).

These brines may occur at the surface, as described by Mianping, Jiayou, Junying and Fasheng (1993), or most commonly within shallow aquifers, as seen in the Andean region of South America (Risacher, Alonso and Salazar, 2003). Lithium concentrations within Andean brines under production range from 0.05 to 0.3% Li, while by comparison, pegmatites display concentrations of 0.7 to 1.8% Li (Evans, 2014; Brown *et al.*, 2016). Grosjean *et al.* (2012) report that concentrations may vary substantially between different basins but also within the same salar, requiring an exploration process lasting two to three years. However, once under operation, the extraction process is very simple and environmentally friendly requiring only pumping and natural evaporation. It is a time-consuming process though, taking as long as two years to produce an end product, such as lithium carbonate or chloride (Grosjean *et al.*, 2012). Of particular importance to brines is the presence of magnesium, expressed as a ratio to lithium, as a higher ratio increases the difficulty in processing (Evans, 2014).

Lithium has also been found to be concentrated in geothermal and oilfield brines where saline groundwater has been enriched at the margins of granitic intrusions. Where geothermal fluids are already being used in power and heat generation, and likewise in oil and gas extraction, lithium is already a by-product as impurities must be removed to prevent scaling and corrosion and provide pure oil and gas.

Thus, its production is energy-free and may be a promising source (Grosjean *et al.*, 2012).

The world's largest source of lithium is seawater, an almost inexhaustible resource, although it only has a typical concentration of 1.7 x 10^{-5} % Li (Vikström *et al.*, 2013; Henckens *et al.*, 2016). This makes it complex and costly to isolate from the variety of other elements, and although much research has been done on this topic, Grosjean *et al.* (2012) report that it remains 10 to 40 times more expensive to extract than from brines (2 to 3 USD/kg) and pegmatites (6 to 8 USD/kg). However, even at this concentration, it has been calculated that more than 2 000 000 Mt of lithium could be extracted (Fasel and Tran, 2005). This would come at a hefty energy cost though, with the extraction of 25 kt of Li requiring around 1 500 TWh of electricity (Bardi, 2010), the equivalent of 6% of the world's electricity produced in 2016 (Enerdata, 2018).

Table 3.2 Summary of lithium deposit types.

Type		Description	Typical Grade (% Li)	Production Cost (USD/t LCE)	Examples
	Pegmatites	Coarse-grained igneous rocks formed during late-stage crystallisation	0.7 – 1.9 %	3100 - 4500	Greenbushes, Australia
Minerals	Hectorite	Smectite clays occurring in sedimentary sequences	0.2 %	1950	Sonora, Mexico
	Jadarite	Altered sediments in an enclosed basin	0.7 %	-	Jadar, Serbia
	Continental	Enclosed basinal brines derived from weathering of volcanic rocks	0.04 – 0.15 %	1200 - 1550	Salar de Atacama, Chile
Brines	Geothermal	Elevated Li-content in geothermal springs	0.01 – 0.035 %	-	Salton Sea, California, USA
	Oilfield	Elevated Li-content in brines found to co-occur with oil reserves	0.01 - 0.05 %	-	Smackover Formation, USA

Source: (Evans, 2014; Brown *et al.*, 2016)

Yet, a recent economic analysis of extracting lithium from seawater via a membrane distillation crystallisation process is contrary to the findings of Grosjean *et al.* (2012). This was undertaken by Quist-Jensen, Macedonio and Drioli (2016) and found that LiCl could be produced at 2.18 USD/kg, which is comparable to continental brine processing and much cheaper than lithium mineral extraction. This would also have the added bi-products of fresh water and other minerals, although requiring immense amounts of energy. Nevertheless, there is no known commercial production of lithium from seawater nor are there plans to do so. This indicates that extraction from seawater is possible if the price incentive is sufficient, but it should not be considered part of the supply curve for planning purposes (Kushnir and Sandén, 2012).

This analysis of occurrences forms the basis for assessing all possible resources and reserves of lithium to establish its availability and global distribution. A summary of these is depicted in Table 3.2, along with their typical grade and production costs, derived from Brown *et al.* (2016) and Evans (2014).

3.2 Historical and Current Supply

There are very few works of literature detailing the commercial side of lithium. Primary production data are either historically poorly recorded, classified or ambiguous due to the multitude of primary products available on the market. However, statistics from the British Geological Survey provide figures going all the way back to 1925 (Brown *et al.*, 2016). This is close to the start of commercial production of lithium in 1923, undertaken by Metallgesellschaft, AG, in Germany via electrolysis (Hart, Beumel and Whaley, 1973). Thus, an almost complete history of lithium commercial production is provided in Figure 3.1, with production data from 2013 to 2015 provided by Hocking *et al.* (2016).

The total historical production of lithium indicated by this data is around 625 thousand tonnes (Brown *et al.*, 2016; Hocking *et al.*, 2016). This compares well with estimates made by Kushnir and Sandén (2012) of 500 kt until 2010, building on estimates made by Andersson and Råde (2001). Current annual production is around 5% of total global cumulative production, demonstrating how rapidly demand has risen in recent years. It also indicates how trivial current societal stocks are in relation to the existing intensity of use (Kushnir and Sandén, 2012).

Production was very limited until the 1950s when lithium became important in nuclear fusion weapons during the cold war (Skene and Murray, 2017). The US dominated the supply market along with some minor Russian production until the early 1980’s, producing around 5 kt Li per annum for most of this period (Figure

3.1) (Maxwell, 2015; Brown *et al.*, 2016). A market shift occurred in the mid-1980s when extraction from continental brines commenced in Chile, adding an extra 2.5 kt annually (Evans, 2014). In addition to this, Greenbushes Mine began processing lithium from minerals in Australia in 1983 (Brown *et al.*, 2016). Production figures rose to almost 13 kt Li in 1997 when other operations were granted mining rights in Chile adding around 3.4 kt Li to global supplies (Garrett, 2004). Processing of brines in Argentina also began in 1997 while all other South American producers extended their production volumes.

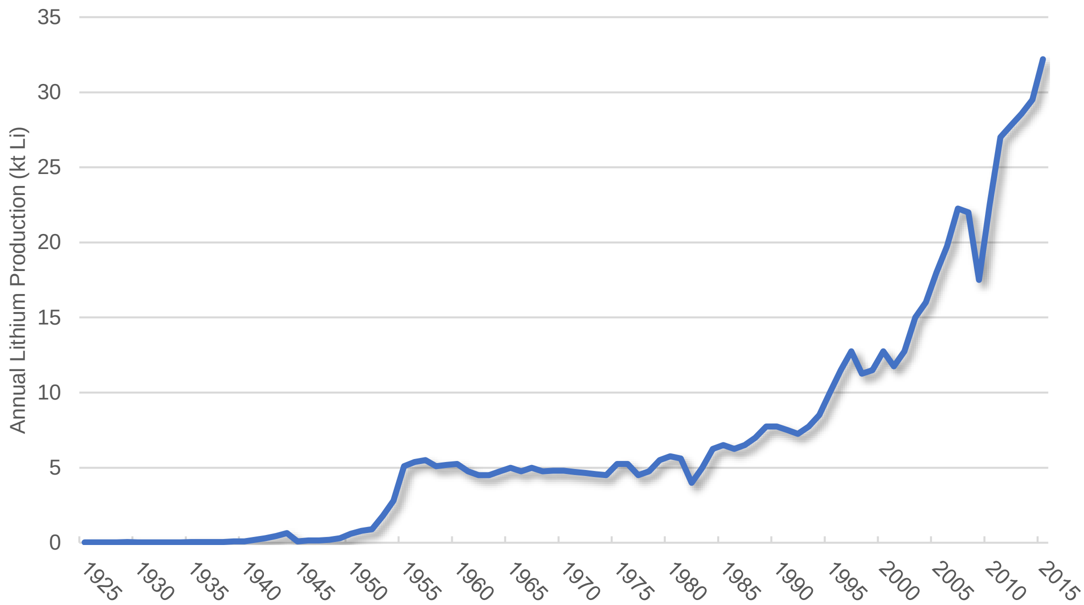

Figure 3.1 Global production of lithium from 1925 to 2015 (Brown *et al.*, 2016; Hocking *et al.*, 2016).

Lithium extraction has almost tripled from 2000 until 2015, to around 32.2 kt Li, due to the expansion of existing operations as well as new capacity (Brown *et al.*, 2016; Hocking *et al.*, 2016). China has gradually increased its market share, producing from a wide array of mineral deposits as well as brines in Tibet (Evans, 2014). Greenbushes mine is now the single largest contributor to lithium supplies, with an estimated 10.7 kt Li in 2015 (Hocking *et al.*, 2016). A correction to this increase in supplies was seen in 2009, due to a drop in lithium prices observed in the previous year (Macquarie Research, 2016).

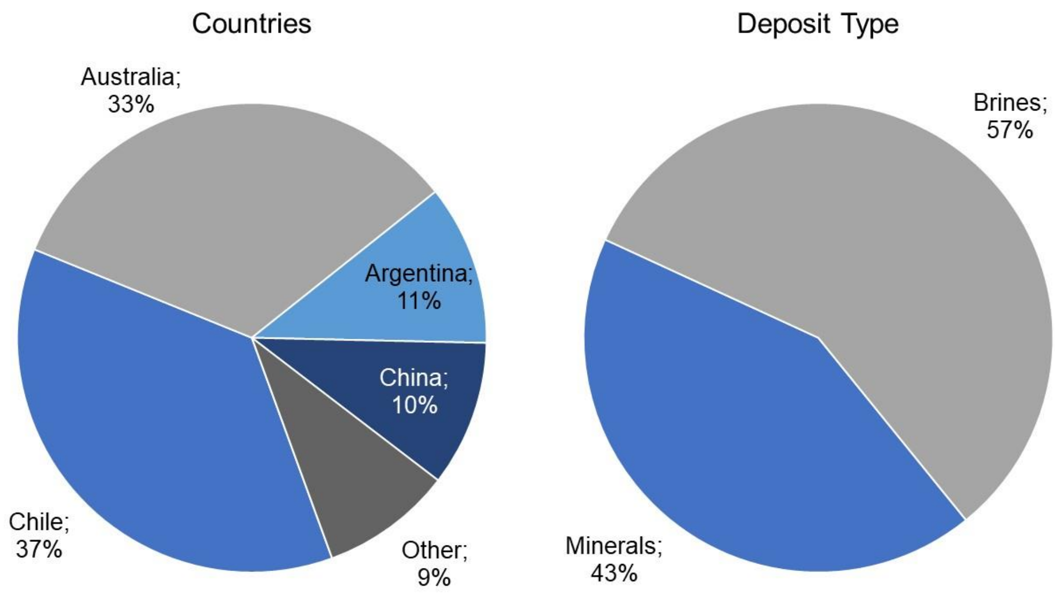

Figure 3.2 Market share of lithium production for 2015 by country and deposit type (Hocking *et al.*, 2016).

Supplies of lithium are highly geographically concentrated, as seen in data reported for 2015 from analysts at Deutsche Bank (Hocking *et al.*, 2016) (Figure 3.2). Production is confined to only eight countries and three of these are responsible for 81% of the world's supplies. Australia and Chile had roughly equal shares, at 33% and 37% while Argentina provided another 11%. China produced an additional 10% of the entire world’s supply and the remainder originated in the US, Zimbabwe, Portugal and Brazil, sharing approximately 9%.

Continental brines are the predominant source of these supplies, representing approximately 57% of the total in 2015, as seen in Figure 3.2 (Hocking *et al.*, 2016). Brines are markedly cheaper to process than lithium occurring in pegmatitic form, starting at 1 200 USD/t LCE while the cheapest mineral deposits have reported figures of over 3 100 USD/t LCE (Evans, 2014). The two to threefold cost of lithium mineral mining is due to the energy intensity required to process hard-rock deposits and is also why brines are likely to remain the primary source of production (Grosjean *et al.*, 2012; Evans, 2014).

3.3 Major Producers

The largest single lithium operation, Talison Lithium, is jointly owned by Albemarle and Tianqi Lithium and is based at the Greenbushes Mine in Australia. Talison produced around 58 kt LCE in 2015, at an average grade of 3 to 4.5% Li_2O, which is upgraded to an average of 6% Li_2O mineral concentrate before being exported abroad. The clear majority of this concentrate, about 90%, is bought up by China where it is further refined into technical grade products (Macquarie Research, 2016). Analysts at Macquarie Research estimate that the mine is producing at less than 60% of its designed capacity, indicating intentional restraint to support lithium prices since it dominates approximately a third of global supplies. Talison also holds 50% equity in Salares Lithium Inc, which is currently developing several brine deposits in northern Chile (Hocking *et al.*, 2016).

Albemarle, a US-owned company formerly known as Rockwood Holdings and Foote Mineral Co., is also responsible for two other operations at Silver Peak, Nevada (US) and in the Salar de Atacama in Chile. These are both continental brine deposits that produced 23 and 4.5 kt LCE in 2015. Combined with its share in Talison Lithium, Albemarle controls about 32.3% of the world's production, the largest entity in the lithium supply market. The high concentration of lithium in the Salar de Atacama, around 0.2%, as well as favourable weather conditions also result in it being one of the lowest cost producers (Hocking *et al.*, 2016). Macquarie Research (2016) suggests that it is producing at approximately 90% its nameplate capacity at its brine operations. It's product, lithium chloride and carbonate, is often destined for South Korea but is also exported to Japan and Europe (Macquarie Research, 2016).

Sociedad Quimica y Minera (SQM) is a Chilean-owned chemical producer that started lithium brine extraction in the Salar de Atacama in 1996, flooding the supply market with cheap products (Evans, 2014). Today, it still operates only a single operation at the lowest market costs as they possess the largest reserves and highest brine concentrations. Around 40 kt LCE of lithium carbonate and hydroxide of various grades was produced in 2015, about 75% of its designed operational capacity. This makes it the second largest producer of lithium products at 23.3% of annual supplies, and its product is typically destined for Europe, Korea, China and the US (Hocking *et al.*, 2016).

Both brine operations on the Salar de Atacama are subject to restrictions on extraction as lithium is considered a strategic metal by Chile, due to its application in nuclear weapons (Hocking *et al.*, 2016). A recent agreement has allowed SQM to extend its production quota of 180 kt Li by 2030 by around 350 kt Li. This allows for a total of 2.2 million tonnes LCE between 2018 and 2030, an average of over 180 kt LCE per annum, which is far in excess of their current 40 kt LCE (Hocking *et al.*, 2016; SQM, 2018). Similarly, Albemarle's quota is for 80 kt LCE per annum but has recently requested that this is extended to 125 kt per year (Reuters, 2017). These agreements are often subject to revised royalty rates or commitments to new technology, infrastructure or other terms that will benefit the economy (SQM, 2018).

The third largest producer, Tianqi Lithium, was solely a Chinese lithium refiner and battery producer until it acquired Talison in 2013, securing brine deposits in Chile and the Greenbushes pegmatite in Australia. Another international interest is in Nemaska Lithium in Canada where Tianqi owns a 9.5% stake in the mineral deposit due to begin commercial production in late 2018 (Hocking *et al.*, 2016). Within in its home country, Tianqi also wholly owns Cuola spodumene mine in Yajiang, which is currently under development, and 20% of the Zhabuye brine in Tibet, which produced 3 kt LCE in 2015 (Hocking *et al.*, 2016; Tianqi Lithium, 2017). Two processing plants with a combined production capacity of 34 kt LCE per annum are located in Jiangsu and Chengdu provinces, with a third scheduled to begin processing 24 kt LCE per annum in Western Australia late in 2018 (Tianqi Lithium, 2017). This places it as an important entity due to its vertical integration as well as representing 17.3% of the world's lithium supply (Hocking *et al.*, 2016).

Another US-based producer, Food Machinery Corporation (FMC), began production from its only operation in Argentina, Salar de Hombre Muerto, in 1997 (Evans, 2010). It was responsible for around 17 kt LCE of supply in 2015, about 10% of the world total, the vast majority of which is consumed internally to produce a variety of speciality grade lithium products (Hocking *et al.*, 2016). Macquarie Research (2016) analysts report that its production facility operates at 85% of capacity and that lithium extraction is not the focus of its operations. Instead, it used to produce a range of agricultural, health and industrial chemicals (Macquarie Research, 2016). The Hombre Muerto brine deposit is widely reported to be of low grade (0.07% Li) but it is aided in its low impurities, which lower its operating costs (Hocking *et al.*, 2016).

Chinese primary production is difficult to quantify as it occurs at numerous mines from dispersed mineral and brine deposits, operated by several different entities. Furthermore, all production is consumed within China with very little information published on sales. However, estimates for 2015 production varied from 10.6 kt kt LCE to 17.7 LCE, the equivalent of around 7 to 10% of world supply (Hocking *et al.*, 2016; Macquarie Research, 2016; Jaskula, 2017; Martin *et al.*, 2017). Hocking *et al.* (2016) report that 70% of the total is derived from spodumene and lepidolite mineral deposits and the remainder is from brines operated on the Qinghai-Tibet plateau.

Orocobre is an Australian and Japanese-owned company that started extracting lithium in 2015 from the Salar de Olaroz in Argentina. Its total production for 2015 was 1.7 kt LCE but it has expanded this to 14.5 kt LCE in 2016 with further plans to double this capacity by 2019 (Hocking *et al.*, 2016; Castilla, 2017). Bikita Minerals produces lithium from petalite in Zimbabwe with an average grade of 4% Li_2O, contributing around 5.3 kt LCE in 2015 (Evans, 2014; Hocking *et al.*, 2016). Portugal and Brazil are the smallest producers of lithium, extracting approximately 3 kt and 2.1 kt LCE respectively from pegmatite deposits in 2015 (Hocking *et al.*, 2016).

When viewing the companies responsible for supply, the situation is just as similar, if not worse than the geographic concentration of production, illustrated in Figure 3.3. Albemarle, SQM, Tianqi and FMC represented approximately 82.8% of the supply market in 2015, although the entry of Orocobre has reduced this in 2016 (Hocking *et al.*, 2016). The lack of diversity has allowed producers to operate well below capacity. Macquarie Research analysts (2016) estimated an average of 82% utilization for the big three brine producers in 2015 (Albemarle, SQM and FMC), while the USGS (Jaskula, 2017) reported only 64% for 2015 and 71% utilization in 2016 for the entire supply market. This has ensured that global production has not met the growing annual demand for lithium products and is interpreted by analysts to be an effort to keep market prices high (Macquarie Research, 2016; Jaskula, 2017).

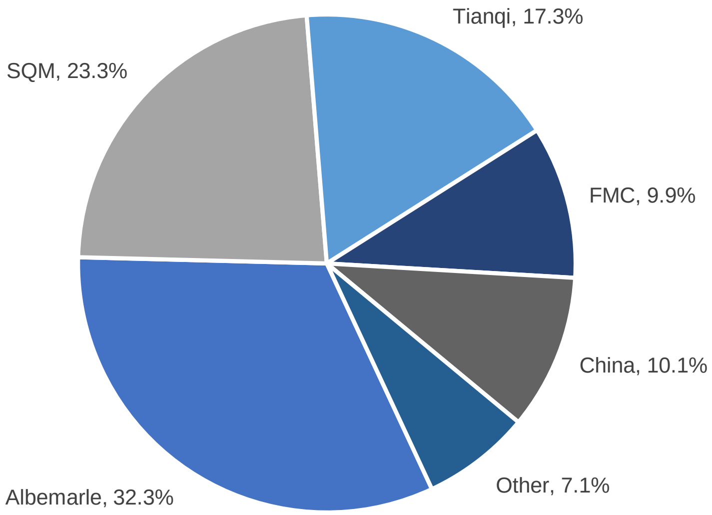

Figure 3.3 Producer share of lithium production for 2015 (Hocking *et al.*, 2016).

As Ebensperger, Maxwell and Moscoso (2005) note, this concentration of production combined with the recent trend in rising lithium prices seems to imply that they are exerting market power, taking advantage of significant barriers to entry and strategically ensuring long-term profits. This behaviour should even be expected when only a few stakeholders control the largest and cheapest resources available (Kesler *et al.*, 2012). Maxwell (2015) refers to this industry situation as an oligopolistic competition where Chinese producers are becoming more prominent. This has been raised as a serious threat to supply security by several authors (Kesler *et al.*, 2012; Vikström *et al.*, 2013; Maxwell, 2015; Martin *et al.*, 2017).

Since 2015, however, other producers have appeared on the scene with several more projected to begin production before 2025. Two pegmatite operations at Mt

Marion and Mt Cattlin in Australia began production in 2016 and are expected to ramp up to 35 and 13 kt LCE per annum respectively by 2018. Additionally, in Australia, two more hard-rock lithium mines are forecasted to be commissioned in early 2018 at Pilgangoora. These are expected to produce a combined 73 kt LCE per annum by 2024. Argentina is anticipated to become a much bigger stakeholder in supplies with the development of brines at Salar de Rincon by Enirgi Group, Cauchari-Olaroz by SQM and Lithium Americas Corporation, and Sal de Vida by Galaxy Resources. This would expand production by a combined 95 kt LCE by 2024 (Hocking *et al.*, 2016).

Production at the Whabouchi pegmatite in Canada began at the end of 2017 and has a stated production capacity of 33 kt LCE. This operation is owned by Nemaska Lithium, of which Tianqi Lithium is a minor shareholder (Nemaska Lithium, 2018). Bacanora and Rare Earth Minerals expect to begin extraction on the Mexican Sonora hectorite and polylithionite deposit in 2019, ramping up to 35 kt LCE in 2021 (Macquarie Research, 2016). The unique jadarite deposit in Serbia owned by Rio Tinto is still under development and exploration but Hocking *et al.* (2016) predict that this will begin production in 2025 of around 20 kt LCE.

These new greenfield projects are all in addition to expansions anticipated to occur in existing operations, which are reported to be an extra 120 kt LCE annually by 2025. Thus, analysts at Deutsche Bank have forecast annual production to be around 548 kt LCE by the same year, equivalent to 103 kt of lithium (Hocking *et al.*, 2016). This is more than a threefold increase in extraction rates in only 10 years. For this reason, attention has been turning to focus on the availability of naturally occurring lithium to determine if it will be sufficient to support this rapidly growing trend in consumption.

3.4 Estimates of Primary Lithium Availability

Known quantities of any commodity may be defined in two different ways, according to The Society for Mining, Metallurgy and Exploration (2014). Resources are defined as concentrations of economic grade with reasonable and realistic prospects of economic extraction. Reserves state the recoverable amount after considering losses or costs due to mining, metallurgical, economic,

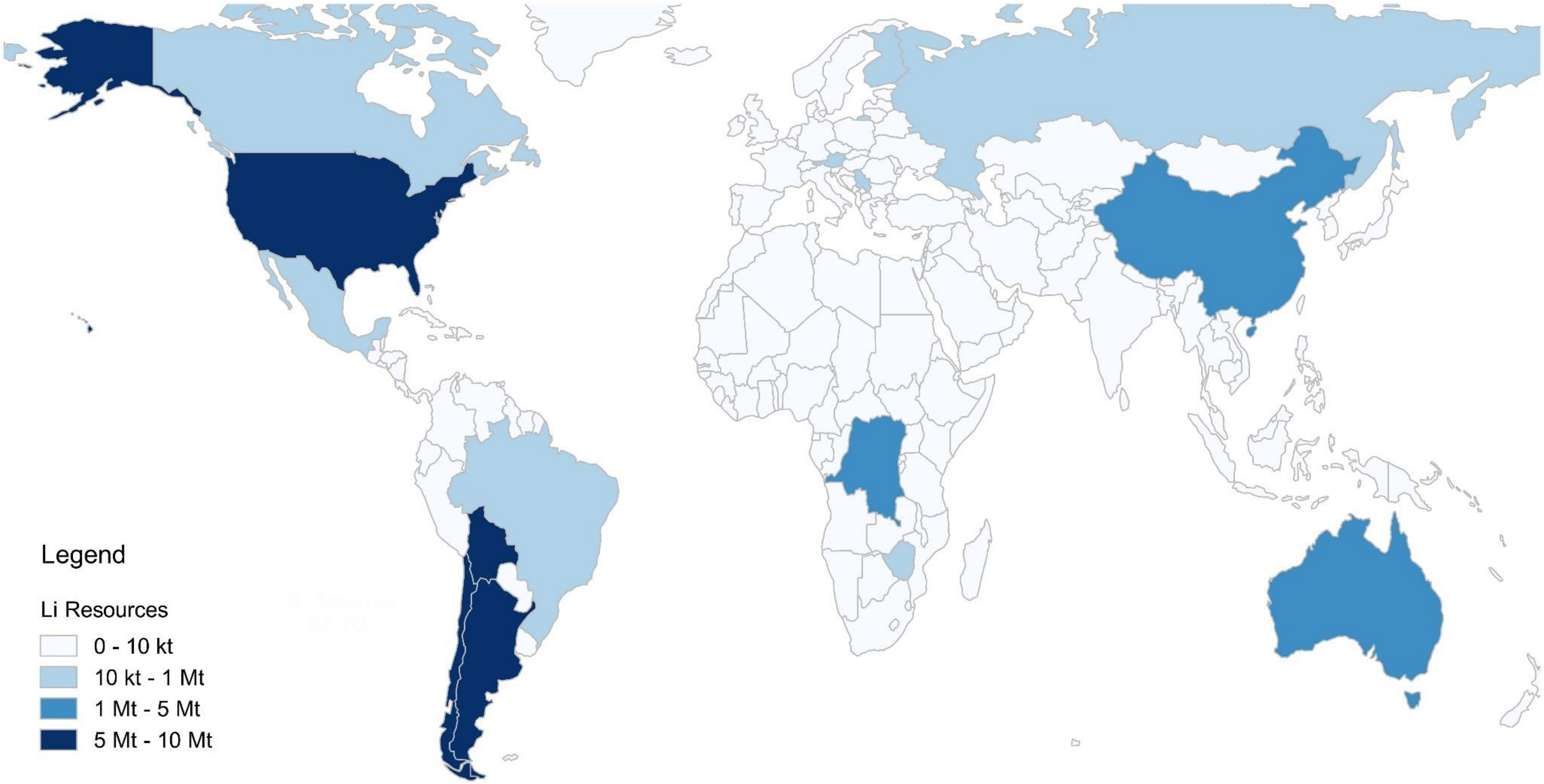

Figure 3.4 World distribution of lithium resources (derived from Evans, 2014).

marketing, legal, environmental, infrastructure, social and governmental factors, and are usually significantly lower than resource estimates. Standardizing these terms provides a broad baseline in order to make comparisons of estimates from different sources.

Considerable work has been undertaken to establish the availability of lithium worldwide. One of the first estimates published only considered deposits in the western world but calculated a total of 10.65 Mt of lithium (Evans, 1978). This was before discoveries of large deposits in South America and China (Evans, 2014). Subsequently, additional work has been done by Kunasz (2006), Evans (2008) and Yaksic and Tilton (2009). The latest iteration of this estimate was conducted by Evans (2014) and reported a global lithium resource of 40.07 Mt, which is represented in Figure 3.4.

It is interesting to note how these estimates have increased over time, however. The USGS placed the resource estimate at approximately 13.76 Mt in 2009 and then increased it to 25.5 Mt a year later (Jaskula, 2009, 2010). Their latest report has almost doubled this figure indicating that 53 Mt of lithium is available worldwide (Jaskula, 2018). Regarding other literature published on the topic, Kesler *et al.* (2012) calculated global resources to be 31.1 Mt, while Tahil (2008) reported it to be at 19.2 Mt, up from estimates of around 12 million tonnes over two decades ago (Ober, 1998). The trend is clear that it has increased drastically over time and this is corroborated by Patiño Douce (2016). Furthermore, he stated that resources will tend to become reserves as demand increases relative to supply, pushing market prices up. This was also concluded by Speirs *et al.* (2014), who conducted a review of all available sources.

As Evans (2014) states, resources may provide a broader understanding of what is economically viable, but many authors discussing this issue neglect to consider that these are not always recoverable. Operations at SQM's brines in Chile recover anywhere between 28 and 40% lithium, for instance, while a new mineral operation coming online in Australia, Pilgangoora, expects a 76% recovery rate (Hocking *et al.*, 2016). Furthermore, losses must also be considered for the variety of other factors mentioned previously in the calculation of a mineral reserve. Thus, estimates of reserves are often much lower than that of resources. The USGS (Jaskula, 2018) reported global reserves of less than a third of their calculation for resources, for example, putting the figure at 16 Mt in 2018. This has also increased markedly over time, with the same institution estimating an available reserve of 3.7 million tonnes in 1998 (Ober, 1998).

Patiño Douce (2016) made an effort to calculate the depletion of lithium beyond 2012 based on historical rates of extraction and estimates of reserves from the USGS. Unfortunately, he applied an incorrect figure of 643 kt for Li produced in 2012 and a linear extrapolation of growth, finding that reserves would be depleted by 2026 or 2027. This linear function does not consider that demand levels off over time. He does, however, mention that if a logistic function is used for all metals, a threefold requirement of reserves estimated in 2012 would be needed by 2050. This extends to three to twelve times present (2012) reserves by the year 2100.

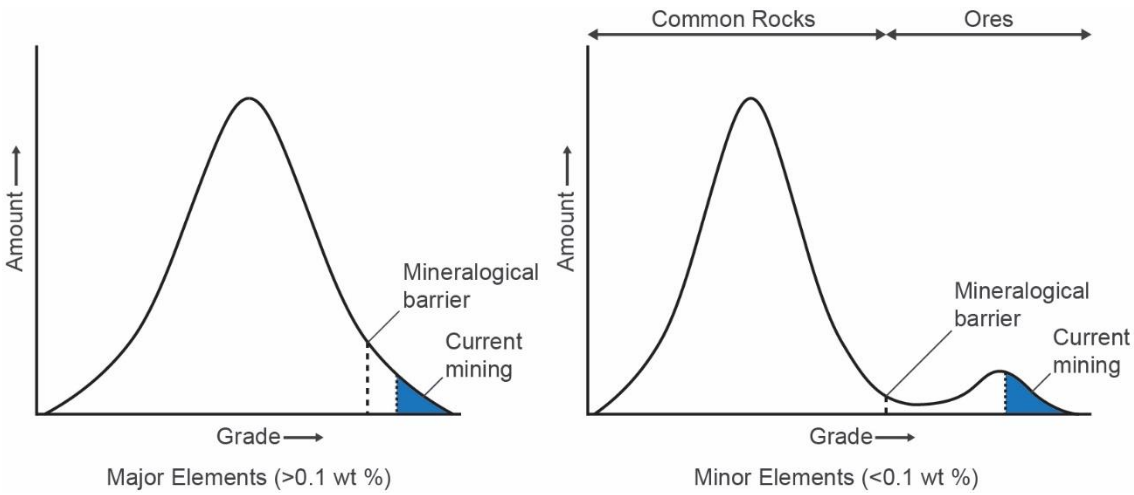

Figure 3.5 Theoretical distribution of major and minor elements within the earth's crust (lognormal), after Skinner (2001).

Rising estimates of the amount of lithium available hints at a flaw in these calculations. Henckens *et al.* (2016) argue that this view of only known resources obscures a realistic determination of availability which should include economic deposits that are yet to be discovered. First, a discussion of the distribution of elements within the earth's crust is relevant. In a seminal paper by Skinner

(1976), it was proposed that geochemically abundant elements (>0.1 wt% average content) have a different distribution to that of geochemically scarce elements (<0.1 wt% average content) within continental crust, as seen in Figure 3.5.

For major elements, their occurrence is unimodal resulting in higher volumes and lower grades as they are depleted until the mineralogical barrier is reached. This is the point at which an element is no longer concentrated enough to justify mining and processing, or economic depletion. For minor elements, however, available volumes will increase at first as grades decline and then decrease as viable ore deposits are depleted due to their bimodal distribution. This he attributed to the fundamentals of ore-forming processes, although purely theoretical (Skinner, 1976).

Following this indication, Rankin (2011) highlighted that the total amount of economically viable deposits is directly proportional to its abundance within the earth's crust. This is the area to the right of the mineralogical barrier which may shift in accordance with market pricing. A higher price would allow for improved cumulative production and greater reserves in the long-run, for example (Tilton and Skinner, 1987). Minor element abundance suggests that only 0.01% to 0.001% of the entire amount occurring in the earth's crust is concentrated sufficiently enough to be economically viable for extraction (Skinner, 1976, 2001; Phillips, 1977; Tilton, 2003).

While only a rough estimate, the United Nations Environment Programme (UNEP) used the upper limit, 0.01%, to determine the total amount of extractable minerals in the upper 1 km of the earth's continental crust (Graedel, Barr, Cordier, Enriquez, Hagelüken, Hammond, Kesler, Mudd, Nassar, Peacey and Reck, 2011). This was approximately 35 times greater than the estimates available from the USGS at the time (Henckens *et al.*, 2016). For lithium specifically, this was 800 Mt compared known resources of 25.5 Mt (Jaskula, 2010; Graedel *et al.*, 2011).

Henckens, Driessen and Worrell (2014) forecasted the extraction rates for each element in 2050 and assumed it would remain constant beyond that, ignoring the impacts of substitution and efficiency. This was then used to determine the time before exhaustion after 2050. Lithium was classified as “not scarce” as it would take approximately 9000 years to exhaust all theoretical economic concentrations (Henckens *et al.*, 2014). The total amount of available lithium may not be quantified until all supplies are exhausted, but it may be safe to assume that the most conservative estimate is that of reserves and the most optimistic is that of the UNEP (Graedel *et al.*, 2011).

On the issue of sustainability and geological scarcity, Tilton (1996) elaborated that there are two schools of thought. The optimistic economists argue that technological advances will continue to ensure that supply meets demand despite poorer grades. The pessimists, however, point out that any extraction of minerals is finite and will at some point be depleted, removing the opportunity for later generations. Technology will improve the available supplies by increasing mining efficiencies and cost-effectiveness of extraction, but it has its limits. The same is true of improving material efficiencies in products and finding substitutes that eliminate the need for a metal. There are inherent restrictions and disadvantages to each of these options. Nickless (2017) argues that focusing on new resources and exploration may be most important for the coming decades, but only if sufficient investment is made in time.

The concern of scarcity was stated by the British economist, Robbins (1932), to be at the root of all economics, but it did not consider different forms of scarcity. Until this point in the section, an effort has been made to quantify the structural availability of lithium in sufficient economic concentrations, but it has been recurrently shown that geological scarcity has very little to no impact on market pricing. It is also inversely true that the market price mechanism is not a reliable indicator of geological scarcity and may not be efficient enough to prevent it from occurring (Farley and Costanza, 2002; Tilton, 2003; Seyhan, Weikard and Van Ierland, 2012; Worstall, 2013; Henckens *et al.*, 2016).

As Henckens *et al.* (2016) denote, economic availability or economic scarcity also considers a variety of other factors that affect the balance between supply and demand, in addition to geological availability, and thus the determination of prices. These may be geopolitics impacting upon mineral production or demand for a technology, substitution, efficiencies, and at a larger scale, industrialisation and urbanisation rates. As the majority of authors concur that the geological scarcity of lithium is not a concern within this century (Gruber *et al.*, 2011; Grosjean *et al.*, 2012; Kesler *et al.*, 2012; Kushnir and Sandén, 2012; Speirs *et al.*, 2014), its economic availability may be of more importance.

Chief amongst these issues is the geological distribution of these deposits, which is depicted in Figure 3.4 and Figure 3.6. According to Evans (2014), South America represents well over half the known resources of lithium, with Bolivia, Chile and Argentina comprising 99% of this total. The ideal conditions in the Altiplano region of South America are where almost 90% of continental brines occur. North and Central America accounts for another fifth of global resources leaving the rest of the world to make up the remaining 23%.

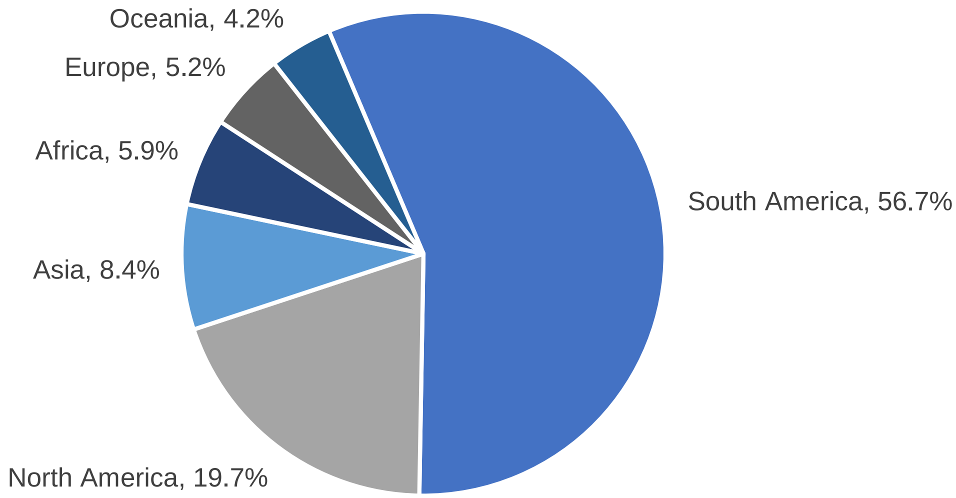

Figure 3.6 Continental distribution of lithium resources, after Evans (2014).

Known pegmatite deposits encompass almost 25% of global resources and are similarly unevenly distributed, with the largest occurrences in North America, the Democratic Republic of Congo (DRC), Australia and Russia (Evans, 2014). Other significant occurrences are hectorite deposits in Kings Valley, USA (5% of total resources), geothermal brines in California, USA (2.5%) and Jadarite in Jadar, Serbia (2.4%) (Evans, 2014). The lack of diversity in their nature and occurrence may only entrench the geological and producer concentrations already observed in the supply side of the market.

In summary, the future availability of lithium could be viewed from three different perspectives. The least of which is in the form of global reported reserves standing at approximately 16 Mt Li in 2018, according to the USGS (Jaskula, 2018). The same institution puts the figure of lithium resources at over 53 Mt Li in 2018 (Jaskula, 2018), while Evans (2014) estimated it to be around 40 Mt Li in an earlier study. These quantities have grown over time with advances in technology and exploration and may be put into perspective with a theoretical calculation of availability. For this purpose, Graedel *et al.* (2011) calculated that 800 Mt Li is economically viable within the upper 1 km of the earth's continental crust.

However, there is a growing resource of lithium that has not yet been accounted for, which may offer respite to this supply concentration and concerns of economic scarcity. As primary deposits are exploited, the amount of lithium in use will rise and as such, the societal stock will increase. This creates a resource that may grow over time as lithium products reach the end of their design life, providing an opportunity to extract lithium from them for re-use.

3.5 Secondary Sources

Recent recycling of lithium products at their end-of-life is reported to be less than one percent and its current contribution to supplies is insignificant (Macquarie Research, 2016; Jaskula, 2017). However, amongst the body of authors that have analysed the availability of lithium, most concur that supplies from recycling will play a growing importance due to rising demand in technological applications as well as regulatory requirements of governments (Peiró, Méndez and Ayres, 2013; Larcher and Tarascon, 2015; Oliveira *et al.*, 2015; Martin *et al.*, 2017). The growing attention to recycling of lithium is reflected by a significant increase in published literature since 2008 as found by Zeng, Li and Singh (2014). They indicate that this is in light of mounting quantities of societal stock and their high content of valuable materials, environmental concerns and the limited capacity of geological reserves.

First, certain theoretical fundamentals of material recycling must be addressed. As Henckens *et al.* (2016) detail, recovery is not possible when a product is used in dissipative applications, such as the application of zinc as an anti-corrosive in steel manufacturing. In this example, the material dissolves in rainwater and is washed away into the environment. Secondly, a material cannot be considered for recycling until it is no longer technically effective in its intended application. Thus, the lifetime of its product is a critical factor in its eventual availability (Grandell, Lehtilä, Kivinen, Koljonen, Kihlman and Lauri, 2016). This issue is exacerbated the growing rates of global urbanisation and development as it locks away a greater proportion of materials. For lithium, it is not as serious as it is for metals such as copper which have a lifespan of over 120 years. However, it remains true that a greater part of societal stock will be tied up as the world's population becomes wealthier (Nickless, 2017).

Thirdly, when a product does reach the end of its technical life, the sale price of recycled material must cover the costs of recycling as well as provide similar or greater profits than primary extraction. If this is not true, mining will remain the predominant source without intervention from governments (Kushnir and Sandén, 2012). Kushnir and Sandén (2012) also point out that recycling cannot satisfy demand while it is increasing or stable. If demand is increasing, existing societal stocks will never be great enough to meet requirements. Even when it has stabilized, virgin resources will still be required to cover dissipative uses of the material in addition to losses due to recycling inefficiencies. This critical point is also substantiated by Nickless (2017) who agreed that primary production will always continue despite recycling.

Of the non-dissipative uses of lithium, such as in aluminium casting and alloys, batteries appear to be the most promising due to their current high market share (Peiró *et al.*, 2013; Martin *et al.*, 2017). Larcher and Tarascon (2015) report that in order to produce a tonne of lithium, only 28 t of spent batteries are required compared to 250 t of minerals or 750 t of brine. Even so, Peiró *et al.* (2013)

indicate that while recycling of lithium batteries is occurring in many countries, operations are primarily focussed on the recovery of rarer and more valuable metals such as cobalt and nickel.

Lithium is used in very small quantities in batteries, around 2 wt%, which is difficult to validate recovery for especially considering that lithium is still inexpensive to mine (Wang, Gaustad, Babbitt and Richa, 2014; Sonoc, Jeswiet and Soo, 2015). Even a recent study of a new recycling process, for example, required virgin lithium carbonate as a reagent to recover other cathodic metals. Any lithium present in the solution was treated as an impurity, although it did achieve recovery rates in excess of 90% for nickel, cobalt and manganese (Gratz, Apelian and Wang, 2014).

Lithium batteries have been in use since the 1990s, but Macquarie Research (2016) argues that there is currently poor financial incentive in recycling batteries used in portable electronics due to their small capacities. For example, the lithium in a typical smartphone equates to only USD 0.02 per battery at 2016 lithium carbonate prices. However, automotive batteries may provide approximately USD 225 for the lithium it contains due to their much greater energy capacity. Gaines (2014) indicates that these have been in use since around 2009 and with an expected life of 10 to 20 years (Wanger, 2011; Peiró *et al.*, 2013; Grandell *et al.*, 2016), these may not be available in large quantities until about 2025. Even when these reach their designed end-of-life, many batteries have historically been refurbished and reused, particularly those of portable electronics, which extends their technical life (Geyer and Blass, 2010).

This highlights another form of secondary supply that may act as an intermediate stage, which is reuse. While applications in EVs require high-efficiency charging and discharging, this is not necessarily the case in static energy storage and several authors have suggested that these batteries may be repurposed for ESS before being recycled (Meeus and Scoyer, 2012; Gaines, 2014; Zeng *et al.*, 2014; Diouf and Pode, 2015). Reuse has the potential to distribute costs over multiple lifetimes and lower their overall environmental impacts. However, several issues have been raised such as the design mismatch between primary and secondary uses, reliability and safety. Manufacturers may also be anxious about the negative public opinion that incidents could create even if their liabilities were signed away (Hein, Kleindorfer and Spinler, 2012; Olivetti *et al.*, 2017).

Broadly, there are two processes currently used to recycle lithium batteries, a high-temperature method, pyrometallurgy, and a low-temperature method, hydrometallurgy, as described by Larcher and Tarascon (2015). The former is significantly quicker and recovers high value metals but does not recover lithium in any form but waste slag as it is not deemed economical (Gaines, 2014). This is the method applied by most of the largest secondary producers at present (Wanger, 2011; Ellis and Mirza, 2014). An exception is Retriev Technology Inc. (formerly Toxco) who use a propriety process known as cryomilling to recover around 15 to 26% of contained lithium before applying the pyrometallurgical method (Sonoc *et al.*, 2015).

Hydrometallurgy has been proven to achieve lithium recovery rates of between 80 to 90% but only on a laboratory scale (B. Swain, 2017). The high yields and low energy inputs for this method are encouraging, although it does require about 7 m^3 of water for every tonne of batteries processed (Larcher and Tarascon, 2015). It also allows more versatility when treating Li-ion batteries of different chemistries. Only two operations are known to be utilizing this method on an industrial scale and are both situated in France, Recupyl and Euro Dieuze. ACCUREC and UVR-FIA in Germany also use hydrometallurgy combined with pyrometallurgy for lithium recovery. However, the yields and recovery efficiencies are not known for any of these hydrometallurgical operations Georgi-Maschler, Friedrich, Weyhe, Heegn and Rutz, 2012; Ellis and Mirza, 2014). Other hybrid processes that focus on pyrometallurgy also combine electrowinning to achieve a greater yield of metals, but this also neglects recovery of lithium (Ellis and Mirza, 2014).

In a study conducted by Wang *et al.* (2014) on the economics of battery recycling, it was found that the profitability of a recycling operation is highly dependent on the composition of the waste stream. LCO batteries are more profitable, for example, because of the high composition and value of cobalt, around 8900

USD/t. For LMO batteries, only 860 USD/t could be expected by comparison. They also determined that volumes of recycling were critical to profitability, with the minimum amount of 170 t/year of LCO batteries required to cover the costs an operation. Thus, it was concluded that recycling and collection policies are necessary for improving the financial incentives of recycling operations. Another study has supported this stance indicating that increased recycling rates will lead to greater profitability (Choubey, Chung, Kim, Lee and Srivastava, 2017). Current recycling operations do not draw a substantial profit to encourage the growth of the market (Heelan, Gratz, Zheng, Wang, Chen, Apelian and Wang, 2016; Macquarie Research, 2016).

The legislation is already in place in the European Union, with collection and recovery rates for Li-ion batteries required to be 45% and 50% respectively as of 2016 (European Commission, 2013). In the USA, only two states have passed legislation that mandates Li-ion battery recycling; New York and California. In China, the greatest consumer, the vast majority of Li-ion batteries are treated as general waste and recycling infrastructure is deemed to be poor (Hao, Liu, Zhao, Geng and Sarkis, 2017). Some studies suggest that producers of batteries need to carry to burden of responsibility until they are properly disposed of or recycled which would be enforced by legislation (Wang *et al.*, 2014). Others have proposed that customers should accept the obligation through a form of sales tax on batteries (Larcher and Tarascon, 2015). However, the consensus is that this mechanism is still lacking and needs to be improved to avoid electronic waste and create a closed loop for the usage of these metals (Zeng *et al.*, 2014).

As the current quantities of lithium recycling are insignificant, authors forecasting supplies from secondary sources have struggled to calculate future flows. Most have avoided reporting data for this or have used hypothetical situations, which may be misleading (Gruber *et al.*, 2011; Wanger, 2011; Macquarie Research, 2016; Sverdrup, 2016). It is further complicated by the varied chemistries of Li-ion batteries that may also change in the future (Sonoc *et al.*, 2015). However, as societal stocks of large Li-ion batteries increase and grades of primary operations continue to decrease, this will eventually lead to greater recycling rates (Peiró *et al.*, 2013; Evans, 2014; Larcher and Tarascon, 2015). This would also reduce supply risks as recycling operations would diversify sources and are not geographically fixed (Habib *et al.*, 2016).

4 MARKET PRICING

Supply and demand ultimately converge in the price formation of a commodity, and in a perfectly open and competitive market, the price should represent what buyers are prepared to pay for and what producers are willing to be reimbursed for their efforts (Tilton and Guzmán, 2016). The determination of commodity prices is not so clear-cut, however, and are often influenced by a variety of other factors. This section seeks to analyse the historical and present prices of lithium and how its price is determined, before looking to other market parallels where price disruption has occurred. These dynamics then need to be applied specifically to the lithium market to understand the various risks that threaten the growth seen in recent years.

4.1 Historical Prices and Price Development

The USGS (Kelly, Ober and Jaskula, 2017) has been monitoring lithium prices since 1952 allowing an interesting analysis of the dynamics of the market. Lithium is typically quoted as technical-grade lithium carbonate with a purity of ≥99.5%, the most traded form, but prices may vary according to location. The prices displayed in Figure 4.1 are derived from US Customs import prices and reflect US prices of LCE, adjusted to real 2017 prices according to published Consumer Price Index data (US Department of Labor, 2017). More recent updates of market prices were derived from Metalary (2017) for the years 2014 until 2017.

Despite the rise in lithium prices in recent years, current prices are still significantly lower than that what it was traded for in the 1950s. After the adjustment for inflation, a falling long-run trend is apparent, consistent with the findings of Yaksic and Tilton (2009). Maxwell (2015) provided an excellent review of how producers play a role in the dynamic between supply and pricing.

Prices stabilized at about USD 8 to 6 per kg from around 1965 until the 1990’s, when two to three significant US producers dominated primary production (Maxwell, 2015; Kelly *et al.*, 2017). During this phase, very little changed in the volume of world production, until a US producer began extraction from brines in Chile and Greenbushes started production in the mid to early 1980s (Evans, 2014; Brown *et al.*, 2016). Despite the production of lithium more than tripling in volume from 1982 to 1997, market prices did not reflect this boom in supplies. (Kelly *et al.*, 2017). Maxwell (2015) refers to this industry status as a cooperative oligopoly, where prices were controlled and consistently published by producers for over 40 years.

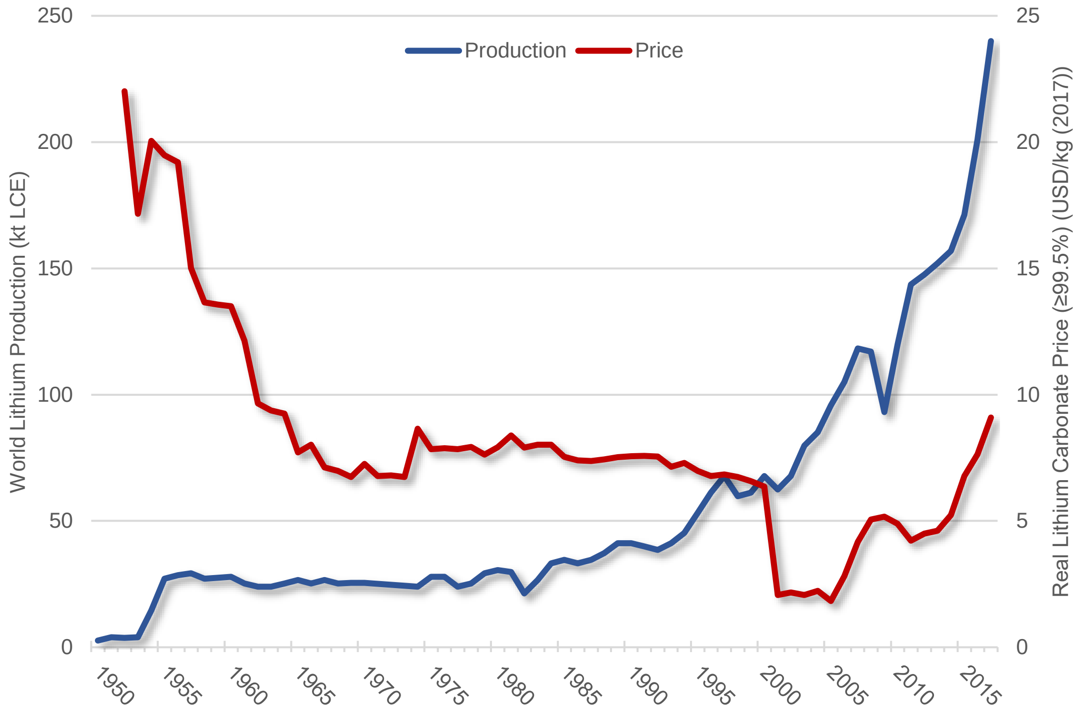

Figure 4.1 Average annual US import price of technical-grade lithium carbonate (≥99.5%) from 1952 to 2017 (Kelly *et al.*, 2017; Metalary, 2017) plotted against world production of lithium carbonate equivalent (Brown *et al.*, 2016; Hocking *et al.*, 2016).

A major change in market conditions occurred in 1998 when SQM began supplying the market with lithium at half the price of its competitors (Maxwell, 2015). This was also reported by Ober (2000), who stated that the “vigorous” entrance of SQM forced other producers to reduce their prices too. Suddenly, prices were no longer cited in corporate announcements and buyers were required to keep the terms of their purchases a secret (Maxwell, 2015). Even Ober (2000) indicated that the published prices of lithium by the USGS were no longer in line with what customers were actually paying, believing them to be much lower. Although not represented in Figure 4.1, customs data from the US showed that values decreased 46% between 1996 and 1999 for lithium from Chile (Ober, 2000). This was eventually reflected in data for the years 2000 to 2005 when average annual prices dropped to approximately USD 2 per kg (Kelly *et al.*, 2017).

Although the entry of SQM resulted in increased competitiveness, it resulted in price opacity out of fear for the loss of market share by existing producers. Maxwell (2015) attributes this to a lack of cooperation between suppliers and indicates that it even delayed the expansion of Argentinean operations. In the most recent period, since 2000, a vast increase in production volumes has occurred and saw a fourfold growth in prices from 2006 until 2017 (Brown *et al.*, 2016; Hocking *et al.*, 2016; Kelly *et al.*, 2017; Metalary, 2017).

The surge in production and prices were interrupted by a global recession in 2008, which caused South American producers to scale back operations in response to lower than expected prices (Macquarie Research, 2016). Stagnant economic growth slowed lithium consumption until mid-2015, resulting in depressed prices in an oversupplied market (Hocking *et al.*, 2016). Two other major contributors appeared in the supply market during this period, Tianqi and Orocobre, with a few others expected in the next five years (Hocking *et al.*, 2016). Maxwell (2015) adds that this has led to even greater competitiveness in the industry with a growing transparency in pricing, although a strong producer control still remains.

An accurate determination of present lithium prices is still quite difficult to attain, with most quotes coming from industry sources that require a subscription, such as Industrial Minerals (2018), Shanghai Metals Market (2018) and Asian Metal (2018). As an industrial metal, this is because bilateral purchase agreements are made between suppliers and processors and prices vary according to each contract (Tilton and Guzmán, 2016). Yet, recent prices are still sometimes made available in the media.

Benchmark Mineral Intelligence estimated that a tonne of technical-grade lithium carbonate (99.5%) was valued at USD 14 000 in South America (Free On Board) at the end of 2017 (Wilson and Biesheuvel, 2017; Jacobs, 2018). The same firm reported a price of 20 750 USD/t for Cost Insurance and Freight (CIF) in Asia (Jacobs, 2018), while Shanghai Metals Market (2018) estimates that the same grade in China was valued at around 26 470 USD/t in November 2017. This is in line with Macquarie Research analysts, who confirmed that Chinese processors offer much higher prices than the rest of the world. These figures are far in excess of Macquarie Research (2016) forecasts of 8 250 USD/t (99.5% CIF China), as well as Deutsche Bank who predicted a fall to 16 750 USD/t (99.5% CIF China) from highs in 2016 (Hocking *et al.*, 2016).

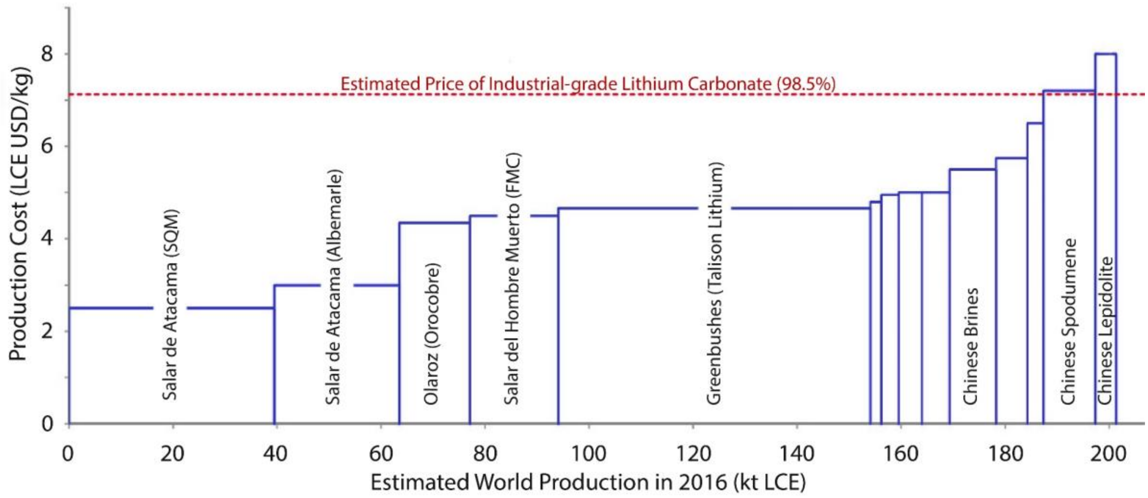

Figure 4.2 Global cost curve of lithium production in 2016 with the estimated price of industrial-grade lithium carbonate (98.5%) indicated (Hocking *et al.*, 2016).

These higher market prices have an impact on supply as it provides greater incentive for more producers to enter the market. In a market report from Deutsche Bank (Hocking *et al.*, 2016), analysts published a global cost curve, seen in Figure 4.2, for estimated lithium supplies in 2016. Their forecasted average price of 7 125 USD/t (CIF China) for industrial-grade lithium carbonate (98.5%) is also displayed. This indicates that total production was expected to be around 201 kt LCE, or around 37.8 kt Li (Hocking *et al.*, 2016). Even at this conservative price estimate, all but ~9% of production fell below the market value, with only Chinese mineral producers deemed to be operating at a loss. Brine extraction in Argentina and Chile has the highest incentive to expand operations as costs are only between 2 and 4 USD/kg. Talison Lithium is marginally more expensive than these South American producers at around 4.60 USD/kg due to its high grades and large reserves (Hocking *et al.*, 2016).

With the latest prices deemed to be between 20 and 26 USD/kg though (Jacobs, 2018; Shanghai Metals Market, 2018), this will encourage existing projects to expand production capacities and more greenfield operations to begin extraction. The supply deficit observed by the USGS and market analysts was expected to be eliminated in 2017 due to new capacity (Hocking *et al.*, 2016; Macquarie Research, 2016; Jaskula, 2017). However, rising prices indicate that demand for lithium has still not been met (Jacobs, 2018).

Many metals are traded on auction at exchanges around the world, such as the London Metal Exchange (LME), the New York Mercantile Exchange and the Shanghai Metal Exchange. Spot prices are determined by what buyers are willing to pay for what is on offer (Tilton and Guzmán, 2016). This mechanism is argued by Maxwell (2015) to be the most transparent and competitive as commodities are available to many buyers and prices are published on a regular basis. Future contracts are also available where commodities are sold at an agreed price for delivery at a specified date in the future. This protects producers and processors from price volatility, but it also allows for investment or speculation by other parties that do not intend to process the commodity (Tilton and Guzmán, 2016). As commodities are increasingly viewed as a financial asset, short-term volatility has been shown to be a function of this trend (Arezki, Hadri, Loungani and Rao, 2014; Le Billon and Good, 2016).

Other metals, however, are not suited for trading on exchanges due to their differentiated nature or relatively small trade volumes. Prices may be negotiated directly between producers and buyers or with the assistance of an intermediary without any need for a formal institutional structure. Lithium prices are currently determined by this mechanism and published prices are a reflection of industry knowledge based on surveys (Tilton and Guzmán, 2016). Maxwell (2015) argues that it is only a matter of time before lithium compounds will be traded in exchanges, given the expected growth of the supply market. Recently, the LME was already reported to be considering offering futures contracts for lithium after requests from buyers (Sanderson, 2017).

It is difficult to present forecasts for prices, as current market values are already significantly higher than estimates of around 7 000 USD/t made by analysts for the years 2022 and 2025 (Hocking *et al.*, 2016; Macquarie Research, 2016; Jacobs, 2018). Complications also arise in the uncertainty of lithium sources from the recycling of societal stocks, without considering a variety of possible disruptions to supply and demand. Thus, it is problematic to state with certainty if current prices will remain as strong or return to a position closer to historical values. However, a perspective may be gained from understanding market dynamics surrounding previous surges in other metal prices.

4.2 Market Parallels

There are several examples of dramatic surges in metal prices in recent history. Habib *et al.* (2016) discussed instances seen in cobalt, platinum-group metals and rare-earth elements markets, while Radetzki (2013) provided an analysis of aluminium and nickel pricing and the drivers behind them. Analysts at Macquarie Research (2016) also indicate that there are very close market parallels in rare-earths and uranium. This section offers a breakdown of the dynamics behind each of these cases in an effort to determine the reasons for their price disruptions and how the lithium market relates to these examples.

4.2.1 Cobalt

The cobalt market is perhaps the most analogous in nature to lithium as it is a minor industrial metal considered to be both strategic and critical in a variety of applications, including Li-ion batteries. Furthermore, its production is highly concentrated geographically and has seen strong demand growth in recent years due to new technological applications (Habib *et al.*, 2016; Shedd, 2018). Traditionally, the largest end-market was in superalloys applied in aircraft engines, magnets and cutting tools, but recently the USGS reports that the largest consumer, China, dedicates 80% of all its supplies to rechargeable battery manufacturing (Shedd, 1999, 2018).

Several instances of price disruptions have occurred in the last 40 years, although the most significant took place in the late 1970s, shown in Figure 4.3. The DRC (then Zaire) and Zambia were then responsible for around two-thirds of global production when political instability hit the region in 1978, shortly after the US restricted sales from its stockpile in 1976. This strife delayed delivery of cobalt at the same time that the global economy was surging and caused demand to increase (Shedd, 1999; Habib *et al.*, 2016).

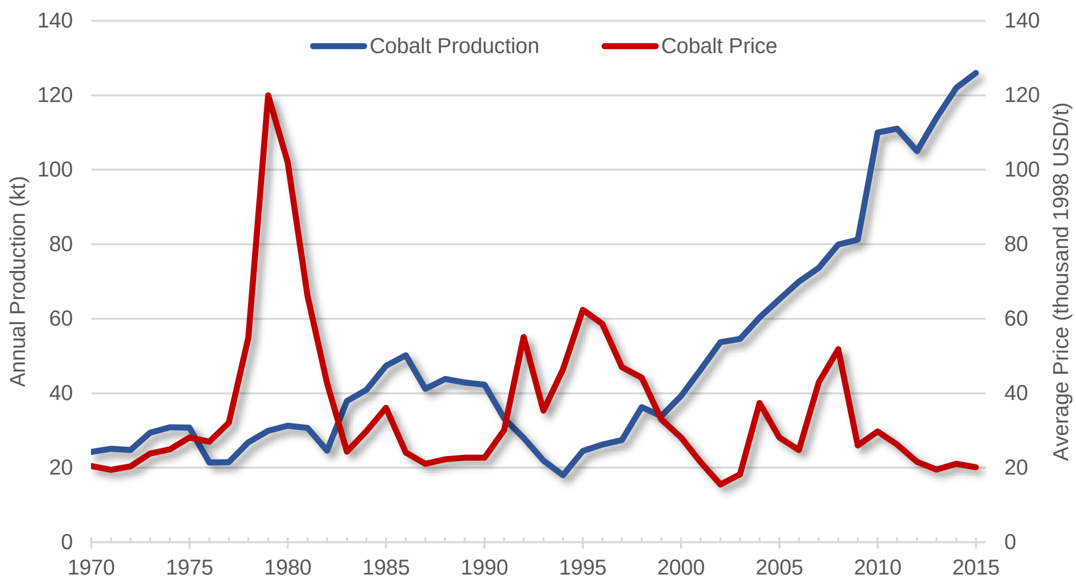

Figure 4.3 Annual production (kt) and real cobalt market price between 1970 and 2015 (1998 thousand USD) (after Kelly and Matos, 2016).

Although production increased during this period, speculation drove prices from 9 410 USD/t in 1976 to 53 300 USD/t in 1979 (Kelly and Matos, 2016). In response, consumers reduced their intensity of use in key applications, built stockpiles, found alternative primary sources and increased recycling rates. For example, Wagner and Wellmer (2009) indicate that consumption in magnets dropped to a third after the crisis. In addition to this, suppliers improved their processing methods to enhance recovery (Habib, 2015). Other instances of rises were observed in the early to mid-1990s and again in 2008 (Figure 4.3), all amidst fears of undersupply due to lowered production in the first case and restriction of exports in the latter (Shedd, 1999; USGS, 2012).

Although the lithium market has not experienced price surges due to supply restrictions, cobalt is an excellent example of how geographic concentration of production renders the market vulnerable to shocks. In these instances, localised geopolitical instability and interference spurred higher prices and was exacerbated by speculation. As detailed previously in section 3.2, the lithium market bears very similar characteristics, with 81% of production focused in Australia, Chile and Argentina in 2015 (Hocking *et al.*, 2016). The history of cobalt market dynamics serves as a strong caution as to how severe the risk of concentration of supplies can be.

4.2.2 Rare-earth elements

Rare-earth elements (REEs) comprise a group of 15 elements in the lanthanide series as well as scandium and yttrium that have unique physical and chemical attributes. These properties have made them highly sought after in a variety of uses, but most importantly in high-performance magnets used in technological applications such as computers, electric vehicles and wind turbines (Massari and Ruberti, 2013). This specific end-use tripled in market share between 1995 and 2007 while world production of rare-earth oxides only increased by around 50% for the same period (Du and Graedel, 2013; Kelly and Matos, 2016). The US, which was the second largest producer in the 1990s, slowed and eventually halted production in 2002 amid environmental concerns and cheaper imports, allowing China to produce 97% of the world's supplies until 2010 (Humphries, 2012).

Citing the priority of domestic demand, the Chinese government began to enforce export quotas of REEs, reducing volumes by 53% between 2005 and 2011. The most significant changes were put in place in 2009 and 2010 and led to widespread panic in both industry and government over supplies (Habib and Wenzel, 2014; Habib, 2015). As a result, prices shot up from 5 290 USD/t in 2007 to 58 100 USD/t in 2011, illustrated in Figure 4.4. This prompted stockpiling, substitution of REEs in manufacturing and increases in recycling and extraction from mines outside of China (Machacek and Fold, 2014; Kelly and Matos, 2016). A case was lodged with the World Trade Organisation, after which China was eventually forced to lift quotas in 2015 (Yap, 2015). Markets for REEs returned to normal ranges long before this, however, once market hype over supply constraints had subsided (Habib, 2015).

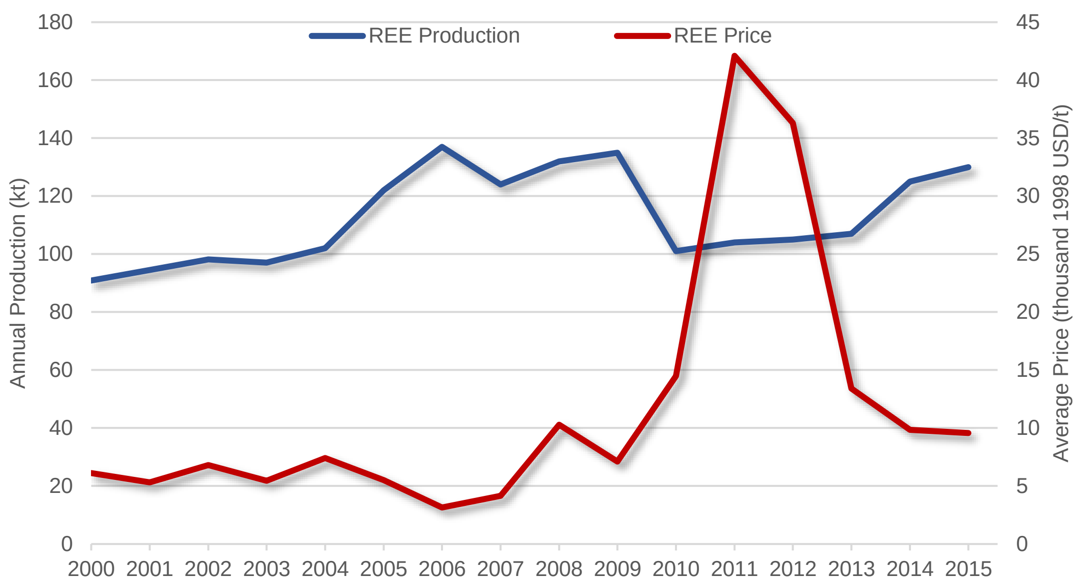

Figure 4.4 Annual production (kt) and real REE market price between 2000 and 2015 (1998 thousand USD) (after Kelly and Matos, 2016).

This example of the REE market is an excellent scenario of how new technological applications and supply constraints can push prices far above their historical levels for a commodity. In the case of lithium, even though production has soared since 2000, levels of demand have also surged due to its use in batteries. Increases in supplies were not sufficient and spurred concerns over availability, causing lithium prices to grow five-fold between 2005 and 2017, as seen in Figure 4.1, on the back of new demand alone. This differs from the case of REEs as lithium production did not decrease, but a deficit in supplies to demand was the concern in both scenarios. New demand as the underlying cause, however, is the same in both markets.

4.2.3 Nickel and Aluminium

Radetzki (2013) highlights the similarities between nickel and aluminium markets from around 1950 until the end of the 1970s. During this period, four North American companies dominated supplies of aluminium, while a single corporation produced most of the world's nickel. They were advantaged by superior resources and held processing patents that created significant barriers to entry by other market players. In addition to this, they were highly vertically integrated and their dominance allowed them to announce market pricing of their products

(Mardones, Silva and Martínez, 1985; Smith, 1988; Radetzki, 2013). Prices increased threefold during this period, displayed in Figure 4.5, although aluminium was more volatile (Kelly and Matos, 2016).

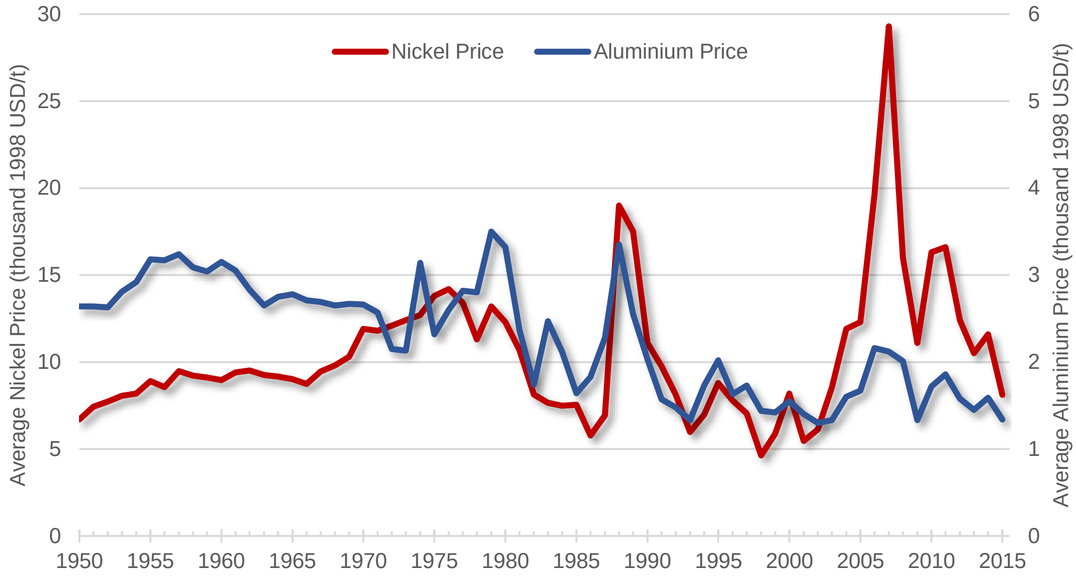

Figure 4.5 Real nickel and aluminium market prices between 1950 and 2015 (1998 thousand USD) (after Kelly and Matos, 2016).

In both producer-controlled markets, their slow disintegration was caused by the emergence of new producers that removed market share. For aluminium, this was driven by nationalisations, while the greater diversity of nickel sources was created by new mining technology (Cairns, 1984; Radetzki, 2013). The listing of aluminium and nickel on the LME in 1978 and 1979, respectively, signalled the start of open pricing and more competitive markets (Radetzki, 2013). Nickel has seen two further price surges in 1988 and again in 2007, both created by supply constraints amidst growing demand (Figure 4.5). The former was caused by a shutdown of many operations in the 1980s due to low prices, exacerbated by export duties imposed by the Dominican Republic, as well as a substantial increase in stainless steel demand (Kuck, 1999). This occurred again in 2007 but almost solely caused by the demand created due to the unprecedented expansion of the Chinese economy (USGS, 2012).

Again, surging demand as well as supply constraints in nickel and aluminium created a concern over metal supply deficits that caused prices to increase rapidly. This serves as another great analogy for the mechanism behind market price increases also seen in the lithium market since 2005, but it also provides another lesson to be learnt. Nickel and aluminium were both producer-controlled markets before their listing on open exchanges, allowing prices to be manipulated by companies that exploited those reserves. Lithium supplies and reserves are controlled by only a few producers in very few countries, as already detailed in section 3, making the market vulnerable to the same manipulation by cartels. This was evident after the market entry of SQM in 1998, forcing prices downwards. However, prices may also increase if all the major producers agree to limit their production or dictate commodity pricing, as in the case of nickel and aluminium until the end of the 1970s.

Markets dominated by less than few producers are susceptible to stakeholder collusion with a view to improving their profits. As Tilton and Guzman (2016) report, there are very few mineral industries that have not been cartelized at some point in history. The success of cartels hinges on their market share of production in addition to the price elasticity of supplies outside of the cartel and price elasticity of demand. They may employ a variety of methods to reduce competition such as price fixing, restrictions on output or enforcing quotas (Tilton and Guzmán, 2016). Two of the most well-known examples are diamonds involving De Beers, and oil in the case of the Organisation of Petroleum Exporting Countries (OPEC). However, this has also been seen in tin, potash and copper, amongst many others, that resulted in large price disruptions due to supply constraints (USGS, 2012; Kelly and Matos, 2016; Tilton and Guzmán, 2016).

4.2.4 Uranium

Uranium presents a very interesting case study, with a large price surges seen in 1978 and in 2007 driven by two different causes (Figure 4.6). In 1971, the US announced a few abrupt changes to its trade policy, amongst which was a ban on enriched uranium imports. Canada had developed a large uranium industry around the needs of the swelling US nuclear energy and weapons market up until that point and abruptly found themselves without buyers (H. Swain, 2017). In response, Canada instigated an agreement in 1972 amongst the foremost producers in France, South Africa, Australia and Gabon to inflate their prices and put pressure on the US market (Martin, 1981; Lichacz, 2007).

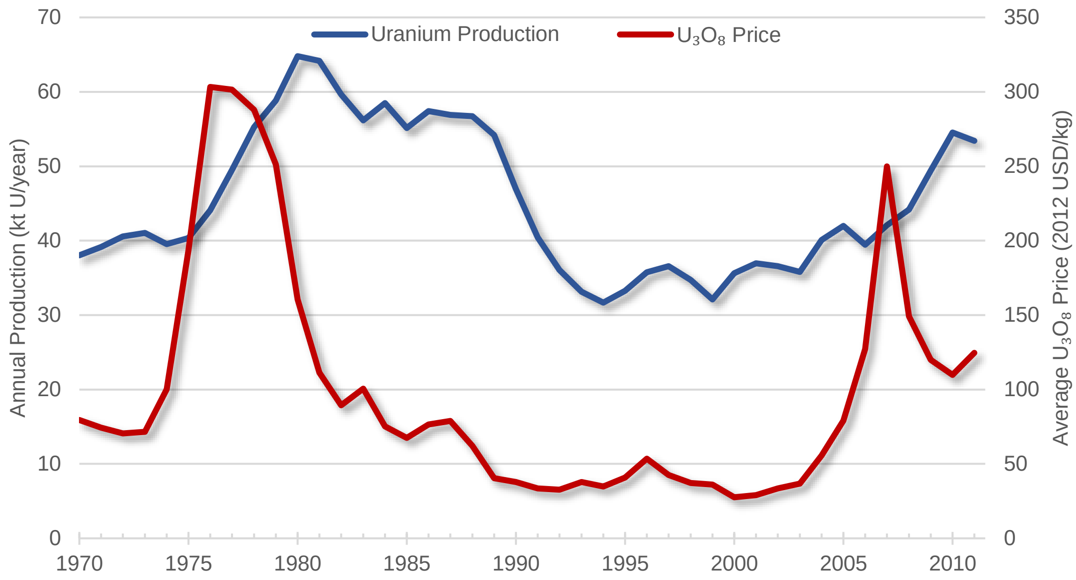

Figure 4.6 Annual production (kt) and real U_3O_8 market price between 1970 and 2012 (2012 USD/kg) (after Pool, 2013).

Until this stage, US nuclear contractors had committed to building several reactors and supplying them with cheap fuel. Very little change in pricing occurred until OPEC embargoed all oil sales to the US in 1973, causing all energy-related commodities to soar in value. In the US, contractors then announced that they could no longer afford primary uranium to meet their obligations and this exacerbated the boom (Martin, 1981; H. Swain, 2017). Uranium went from 13 USD/kg in 1973 to 88 USD/kg in 1978, before it slumped following the inception of European refining facilities and the Three Mile Island nuclear disaster (Mudd, 2014; Cole, 2015). A much larger yet short-lived surge was seen in 2007 to around 300 USD/kg after growing demand for cleaner energy and supply disruptions in Canada and Australia (Mudd, 2014; Cole, 2015).

The price disruption seen in the late 1970s for uranium is an extreme example of how producer-control, or cartelization, can impact the market and serves yet another warning for the lithium supply situation. The second price shock in 2007 was driven by demand that is very closely linked to the lithium market, new applications in the clean energy sector. This is a fairly recent trend that has improved demand for metals that may be utilized in the interest of lowering greenhouse gas emissions.

4.2.5 Platinum Group Elements

The growing desire to move towards lower emissions, encouraged by governmental policy, has also been observed to drive demand and prices up for several minor metals. This has already been see in the cobalt market through its application in batteries, as well as REEs that are required in wind turbines and electric vehicles. However, it is also apparent in platinum-group metals (PGMs) in addition to silver, tellurium and indium markets (Grandell *et al.*, 2016). The latter three elements, all vital in the manufacturing of solar panels and other electronics, saw a large price surge in 2011 and 2012 due to a substantial technological demand increase (Tolcin, 2013; Anderson, 2016; Katrivanos, 2016; Kelly and Matos, 2016).

Platinum, rhodium and palladium, all PGMs, fulfil a different role in clean energy as they are widely and interchangeably used in automotive catalytic converters to reduce emissions from vehicles (Grandell *et al.*, 2016). Increasing legislation in the US surrounding vehicle emissions in the 1990s, as well as reduced exports from Russia, resulted in soaring palladium prices in 2000 (Habib *et al.*, 2016). This was observed again in the 2000s, peaking in 2008, for all three PGMs amidst surging demand in the automotive industry and supply shutdowns in South Africa (USGS, 2012). Loferski (2018) reports that this is taking place again at present and will continue to do so as long as legislation on emissions becomes stricter.

As governmental policies and legislation on levels of emissions become stronger, as well as public interest in lowering impact on the environment, clean energy will become a more important issue in the future. Heavily linked to this is lithium’s application in batteries that may serve to create more efficient and cleaner energy sources. This will generate even greater demand that may put it at risk of price shocks seen in the PGM market.

4.2.6 Causes of Disruptions

Although these examples do not represent every example of metal price surge in recent history, there are several deductions that may be made from these situations. Geopolitics is the most common driver behind all these scenarios and occurs on both the supply and demand side of the market. Production of metals is particularly susceptible when it is concentrated in only a few geographic regions or corporate entities. Constraints may occur by design through monopolies, cartels or governments restricting production or exports of a commodity, seen in uranium, REEs, nickel, aluminium and potash (USGS, 2012; Radetzki, 2013; Cole, 2015; Habib, 2015). It may also transpire coincidentally through political strife, mining accidents or due to environmental concerns, but this is not typically a bid to manipulate the markets. Cobalt in the DRC in the 1970s and PGMs in South Africa in the late 2000s are both prime examples of this (USGS, 2012; Habib *et al.*, 2016).

Price disruptions may also occur due to policies driving demand for certain metals, as seen in the case of governments encouraging the implementation of cleaner energy sources or emission controls. This arose in uranium, REEs, PGMs, cobalt and other minor industrial metal markets such as silver (USGS, 2012). There are some exceptions, like nickel, where economic growth in China caused price surges in 2007 and it is likely this factor played a role in many of the other examples to some degree (USGS, 2012; Tilton and Guzmán, 2016). Speculation by investors is also a growing trend behind rapid changes in market values, which Shedd (2018) deemed to contribute to the recent cobalt prices. By understanding these market dynamics, in addition to the factors of substitution and material efficiencies discussed previously, the various risks specific to the lithium market need to be determined.

4.3 Lithium Market Risks

Most literature published on the risks to lithium markets is primarily concerned with the issue of supply constraints and resource availability in light of growing demand (Yaksic and Tilton, 2009; Gruber *et al.*, 2011; Grosjean *et al.*, 2012; Kesler *et al.*, 2012; Kushnir and Sandén, 2012; Peiró *et al.*, 2013; Vikström *et al.*, 2013; Speirs *et al.*, 2014; Olivetti *et al.*, 2017). However, there are possibilities of demand destruction that are pointed out by market analysts (Hocking *et al.*, 2016; Macquarie Research, 2016), which hark back to Roberts' (1992) lessons of material efficiencies in aluminium and substitution in tin markets.

Other risks may lie in the manner that lithium prices are determined. As Maxwell (2015) reports, the listing of lithium on exchanges may be imminent and could improve price competitiveness and stability, but would also introduce speculation (Radetzki, 2013; Olivetti *et al.*, 2017). There is also the question of when levels of recycling could become significant enough to improve supplies, in addition to whether any other metals involved in the manufacture of Li-ion batteries are vulnerable to supply constraints (Olivetti *et al.*, 2017). This section aims to analyse the factors that may impinge on the growth of the lithium market seen in recent years before an assessment of outlook can be undertaken.

The most prevalent issue is that there are only a small number of critical resource locations, as Kushnir and Sandén (2012) state, and as demand increases, our dependence on them will rise. Chile, Argentina and Bolivia account for about 56% of the world's resources (Evans, 2014), but are all perceived by the mining industry to possess forms of institutional risk. Chile has improved its investment attractiveness in recent years but still faces criticisms over its mineral practices, with stakeholders citing uncertainty and problems with the legal system (Jackson and Green, 2017). Argentina has some of the least attractive jurisdictions in the world, with the northwest Jujuy province important for lithium production, coming 103rd out of 104 entities for mineral practices. Bolivia has also consistently ranked in the lowest quartile for attractiveness in the last five years (Jackson and Green, 2017).

Producers in Chile have been forced to renegotiate their extraction quotas with the government due to lithium’s status as a strategic metal, but these rights have also been put into question during disputes (Hocking *et al.*, 2016). Calls to terminate SQMs lease recently occurred due to supposed inconsistencies in their payments of royalties (Macquarie Research, 2016). This has since been resolved and the quotas increased but it serves as a warning to how vulnerable supplies may be to politics (SQM, 2018). Bolivian resources may be the largest in the world, but they possess magnesium contents three times higher than brines in neighbouring countries. Consequently, these are considered unprofitable to process, intensifying the issue of geographic concentration of resources (Macquarie Research, 2016).

Kushnir and Sandén (2012) hypothesize that if any interruption or restriction of supplies occurred in the Atacama due to political or producer interference or unforeseen production losses, then a large portion of supplies would need to be replaced. As discussed previously, this has already occurred in many other metal markets, resulting in dramatic price surges, as in the cases of cobalt and REEs (Habib *et al.*, 2016). Tilton and Guzman (2016) indicate that geographic concentration of deposits is also made more vulnerable when considering elasticity of supplies, a factor that describes the ability to respond to change. Brine extraction is highly inelastic, taking as long as two years to produce lithium, making these operations very slow to respond to market changes or resume production in the case of an interruption (Garrett, 2004; Topp, Bloch, Soames and Parhan, 2008).

Mineral processing operations are able to improve their outputs far more quickly, but it is unlikely that they would be able to replace the large capacity of South American producers, which was around half of the global production in 2016 (Grosjean *et al.*, 2012; Hocking *et al.*, 2016; Tilton and Guzmán, 2016). Hocking *et al.* (2016) point to new brine processing technology being used in Argentina that significantly shortens the production process thus improving elasticity, however, its economic viability is yet to be determined.

The alarm has been raised over possible supply constraints in other metals used in Li-ion batteries as this would also impact the demand for lithium if these batteries become less cost competitive (Olivetti *et al.*, 2017). Over half of the annual global production of cobalt is used batteries and is required in variable proportions in all of the highest performance Li-ion batteries; LCO, NCA and NMC (Macquarie Research, 2016). Furthermore, around 59% of supplies in 2017 originated in the DRC, a region that often experiences political instability (Jackson and Green, 2017; Olivetti *et al.*, 2017; Shedd, 2018). The distribution of cobalt production is illustrated in Figure 4.7, clearly indicating the dominance of the DRC in supplies (Shedd, 2018). The price of cobalt more than tripled in 2017 in response to growing demand and fears of supply constraints (LME, 2018; Shedd, 2018).

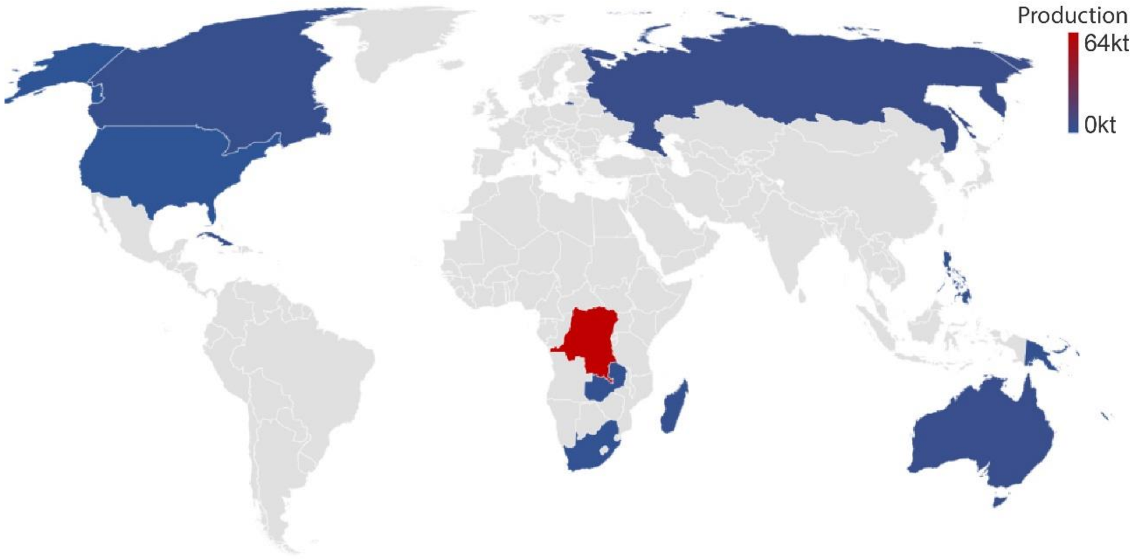

Figure 4.7 Global distribution of cobalt production estimated for 2017 (Shedd, 2018).

Cobalt may be substituted in Li-ion batteries by iron-phosphorous or manganese, but at the cost of performance (Nitta *et al.*, 2015; Shedd, 2018). New chemistries such as NCA and NMC have reduced the intensity of use by as much as six times, but the highest capacity Li-ion batteries still require at least 9% cobalt in within their cathode (Macquarie Research, 2016). To completely eliminate the reliance on cobalt, researchers have focussed on the development of large capacity Li-O_2 or Li-S batteries, although their commercial introduction may yet be a long way off (Bruce *et al.*, 2011; Larcher and Tarascon, 2015). Analysts at CRU Group predict that recycling is set to boom due to supply concerns, expanding from 9.7% in 2017 to 17.9% of all cobalt supplies in 2025 (Harvey, 2017).

Very little recycling of lithium occurs at present, so it is difficult to estimate when it may become a significant source. However, industry analysts at Creation Inn (2017) suggest that 30 kt LCE per annum could be expected to be produced from recycling by 2025. This would equate to around 5% of total forecasted world supplies, around the same as the predicted annual growth in demand for the same year (Hocking *et al.*, 2016). Speirs *et al.* (2014) indicate that more targeted legislation and financial incentives are required if a greater proportion of recycling is to be achieved.

Market pricing is also a function of demand, which is linked to the growth of the economy, the proportion of the economy that the product comprises as well as the material composition of the product, or the amount of lithium required in a product (Roberts, 1992; Tilton and Guzmán, 2016). The price elasticity of demand describes the change in market price that occurs in relation to a change in demand (Tilton and Guzmán, 2016).

Lithium demand is highly price inelastic as there is little room for producers to use substitutes or improve efficiencies beyond the current rates, especially in battery manufacturing (Macquarie Research, 2016; Martin *et al.*, 2017). In addition to this, very limited stockpiling of lithium occurs and is typically consumed almost as quickly as it is produced (Evans, 2014; Hocking *et al.*, 2016). The US, for example, only stockpiles the equivalent of around 6% of its annual consumption of lithium (Macquarie Research, 2016; Jaskula, 2018).

A study undertaken by Ciez and Whitacre (2016) found that large fluctuations in the price of lithium, up to 25 USD/kg LCE from 7.50 USD/kg, would only increase the cost of Li-ion batteries by less than 10%. This is due to the relatively small proportion that it comprises in the costs of manufacturing these batteries. At the time of the study in 2016, it was found that lithium was responsible for approximately 3% or less of the cost. While this price increase is around the levels observed in 2018 (Jacobs, 2018), any further increases were suggested to be unsustainably high for battery manufacturers who already operate under narrow profit margins. In response, supply would need to expand and seawater extraction may even be considered (Ciez and Whitacre, 2016).

As discussed previously, accords such as the Paris Agreement are driving governments to enforce policies that actively encourage the growth of clean energy. This is improving the market share of Li-ion batteries and will continue to do so unless these policies are abandoned, or a more practical substitute is found (IEA, 2017b). Analysts agree that while this is a risk to demand, competing technologies are at least 10 years away from being commercially viable and a major shift to cleaner energy is almost inevitable (Hocking *et al.*, 2016; Macquarie Research, 2016).

The way prices are determined could present other risks to the lithium market. While metal exchanges are often argued to provide an equilibrium between supply and demand on a daily basis, they also introduce the facility to speculate by third parties. In effect, this may result in price volatility beyond what would normally be expected, removing the availability of supplies if prices move beyond what buyers can realistically afford (Radetzki, 2013). Furthermore, Tilton and Guzmán (2016) report that there have been instances in zinc and tin markets where exchange prices were manipulated by producers to keep them above their competitive levels. Thus, there are also inherent dangers if the lithium market had to move from bilateral agreements to commodity exchanges.

This provides a consideration of the various risks that lie in the dynamics of demand, supply and price determination in the lithium market. The outlook for lithium and its growing end-use in rechargeable batteries is innately dependent on these factors, and thus, cannot be forecasted without drawing attention to them.

5 BALANCING FUTURE DEMAND AND SUPPLY

The ultimate question of this research report is to understand if the emergence of new demands for lithium in EVs and ESS will outstrip its availability in the future. This issue has been visited in several published papers originating from both academia and industry. This section will first consider the findings and shortfalls of these studies before making assumptions on supply and demand based on the review of available information discussed previously. This will allow an estimation of the balance between these factors. While many of the risks to the market may be considered, these can be difficult to quantify or state with certainty if they will occur. As such, the various limitations of the predictions of this research must also be reported.

5.1 Findings of Previous Studies

A summary of several studies that aim to quantify the difference between demand and supplies is presented in Table 5.1, indicating whether the authors determined if there was a supply constraint to lithium demands according to their chosen time horizon. While this may not be an exhaustive list of studies undertaken, it does provide an overview of the findings of commentators on this subject. The earliest of this literature coincides with the emergence of the EV sector when concerns were beginning to be raised about the future of lithium availability for this larger application (Vikström *et al.*, 2013; IEA, 2017c).

A common factor in the studies until 2012 is the long period in which they chose to forecast the market, up to 2100, with Sverdrup (2016) also adopting this approach. More recent academic contributions have significantly shortened this window to 2050 or 2030 (Vikström *et al.*, 2013; Evans, 2014; Speirs *et al.*, 2014; Martin *et al.*, 2017), while industry analysts have hesitated to offer predictions beyond 2025 (Hocking *et al.*, 2016; Macquarie Research, 2016). Some authors have offered insight into this, citing that various uncertainties regarding diffusion and material intensity of Li-ion batteries and threats of substitution, for example, make estimates increasingly inaccurate in long-term forecasts (Evans, 2014; Speirs *et al.*, 2014). Thus, caution should be taken when using data taken from papers considering a

Table 5.1 Summary of several studies that analyse the balance of lithium supply and demand.

Author(s)	Study Year	Demands Considered		Supplies from Recycling	Supply Constraint on Demand	By Year	Comments
		EV	ESS				
Vikstrom and Tilton	2009	Yes	No	Yes	No	2100	Seawater acts as a backstop for supplies.
Gruber *et al.*	2011	Yes	No	Yes	No	2100	Recycling is essential. Production facilities need to expand, and new sources are required.
Grosjean *et al.*	2012	Yes	No	No	No	-	Price increases won't destroy demand. Geopolitics and inelasticities could result in shortages.
Kesler *et al.*	2012	Yes	No	Yes	No	2100	Geopolitics are a concern. Recycling is necessary to satisfy demand growth.
Kushnir and Sandén	2012	Yes	No	Yes	No	2100	Policy support is required to improve recycling. Geopolitics and material dependence a concern.
Peiró *et al.*	2013	Yes	No	Yes	No	2020	Recycling important for cobalt, nickel and lithium supplies.
Vikstrom *et al.*	2013	Yes	No	No	Yes	2050	Geopolitics are a concern, recycling is important, and substitutes are needed.
Speirs *et al.*	2014	Yes	No	No	No	2050	Large uncertainties exist regarding lithium intensity and market share of EVs.
Evans	2014	Yes	No	No	No	2030	Supply requires large-scale expansion beyond 2020. Substitutes a threat to Li-ion batteries.
Sverdrup	2016	Yes	No	Yes	No	2100	Recycling is the most important issue in supply. Cobalt is a serious supply concern.
Macquarie Research	2016	Yes	Yes	No	Yes	2021	No physical supply constraints. Producers should meet the demand to keep new entrants out.
Hocking *et al.*	2016	Yes	Yes	No	No	2025	Supply needs to triple by 2025 to satisfy a predicted six-fold increase in EV sales.
Martin *et al.*	2017	Yes	No	No	No	2020	Geopolitics and concentration of supplies are a concern. Substitutes may destroy demand.

Source: Various sources are indicated above.

distant horizon. However, these are not without significant merit and may be valued for their more hypothetical arguments.

All of these studies focus on the emergence of demands from EVs, but only more recent analyses from industry attempt to quantify the requirements of rechargeable batteries in the ESS market (Hocking *et al.*, 2016; Macquarie Research, 2016). This may be attributed to Li-ion batteries only finding sector dominance in installations as recently as 2013, with less than 1 kt LCE consumed in this application for 2016 (Hocking *et al.*, 2016; IEA, 2017b). Yet, both reports present strong cases for ESS becoming a major end market for lithium before 2025 and are supported by findings of the IEA (2017b).

The inclusion of potential supplies originating from recycling operations in forecasts appears to be a controversial concept. Around half of these papers have omitted this consideration on the basis that either secondary production is too uncertain to estimate, or that quantities will remain insignificant in the near future (Vikström *et al.*, 2013; Evans, 2014; Speirs *et al.*, 2014; Macquarie Research, 2016; Martin *et al.*, 2017). Research from two of these sources, Hocking *et al.* (2016) and Grosjean *et al.* (2012), neglect to even regard this possibility. Nevertheless, amongst the authors on this topic, recycling is viewed as important and even necessary to contribute towards growing levels of demand (Kushnir and Sandén, 2012; Vikström *et al.*, 2013; Sverdrup, 2016).

The overwhelming majority of these publications concluded that supply of lithium would not be a limiting factor to demand within each of their respective timeframes. Reserves and resources were deemed to be sufficient and any shortfalls in production could be met by expansion of existing operations or development of greenfield deposits. However, geopolitics and geographic concentration of reserves are recurrently addressed as a major issue, with the inability of producers to respond to rapid demand changes also raised (Grosjean *et al.*, 2012; Kushnir and Sandén, 2012).

Two exceptions to this consensus were Vikström *et al.* (2013) and analysts at Macquarie Research (2016), who found supply deficits as early as 2021 and 2019, respectively. The report by Macquarie Research, though, did indicate that capacity at existing operations is already sufficient to provide for this shortfall and new projects were “likely” to begin extraction of three times that figure. Vikstrom *et al.* (2013) provided a well-founded model of future production based on available information at the time, but present annual production already matches their high reserve scenario which was regarded to be a hypothetical case (Jaskula, 2018). Furthermore, reports from industry on new capacity expected before 2025, based on producer and explorer announcements, is approximately 40% higher than their statistically modelled results (Vikström *et al.*, 2013; Hocking *et al.*, 2016; Macquarie Research, 2016).

This is, of course, the danger when attempting to predict the course of consumption when new applications are still emerging and gaining market share. Despite the best efforts and abilities of these authors, all estimations of relatively new end-markets will carry a large degree of uncertainty. If the demand for a metal is over and above what is expected, producers should naturally strive to meet this by improving their capacity, especially if the price incentivizes it (Tilton and Guzmán, 2016). This mechanism will be discussed in more detail at a later point in this chapter, however.

5.2 Research Assumptions

To enable a prediction of supply and demand of lithium, validated assumptions must be made based on the review of the information undertaken previously and applied to an appropriate time horizon. As aforementioned, studies that attempted to make estimates for 2050 and beyond are susceptible to large uncertainties. On the other hand, authors that do not make forecasts beyond 2025 provide a very limited view of the future balance of the markets and do not consider potential production from the recycling of societal stock. For these reasons, it seems appropriate to adopt a more intermediate horizon of 2030 for the calculations of this report.

Many publications on the topic of supplies only consider an aggregate of available lithium in the form of a resource or reserve estimate, such as Kesler *et al.* (2012) and Gruber *et al.* (2011). This is practical in determining when scarcity may occur, but it does not factor in the ability of producers to expand capacity or to establish new mines. With regards to future lithium production, only a few sources offer predictions, and these are summarised in Table 5.2. The offering from Vikström *et al.* (2013) appears to be too low, while Evans (2014) may be overly optimistic when compared to other calculations. Forecasts from Hocking *et al.* (2016) represent a middle ground, providing figures until 2025 based on industry data.

Table 5.2 Summary of annual production estimates between 2020 and 2030.

Author(s)	Study Year	Production Estimates (kt LCE/year)		
		2020	2025	2030
Vikstrom *et al.*	2013	170 - 229	197 - 298	223 - 372
Evans	2014	593 - 643	-	-
Speirs *et al.*	2014	319 - 585	-	-
Macquarie Research	2016	237 - 417	-	-
Hocking *et al.*	2016	358	548	-
Martin *et al.*	2017	290	-	-

Source: Various sources are indicated above.

The growth rate of supplies is predicted to slow from 2018 stabilizing at 5% in 2025 in response to slowing growth rates of demand and a predicted fall in lithium prices (Hocking *et al.*, 2016). While lithium prices continued to rise in 2017, lower growth rates of supply were also expected by Vikstrom *et al.* (2013) and Macquarie Research (2016). This is inherent in the logistic function, used by Kushnir and Sandén (2012) and Mohr, Höök, Mudd and Evans (2011) amongst many others to predict trends of the production of minerals. For this study, the growth rate of 5% per annum will be adopted beyond 2025 to find production rates in 2030, which is calculated to be approximately 699 kt LCE per year, derived from Hocking *et al.* (2016). Physical availability of lithium is not a concern of this research as the latest estimates from the USGS, of 16 Mt Li in reserves, would allow at least another 50 years of extraction using the adopted growth in production (Hocking *et al.*, 2016; Jaskula, 2018).

On the demand side, forecasts of the EV industry from eight different studies have already been presented in Table 2.3. The sales estimates of electric LDVs vary drastically making it appropriate to use the median values for each year to avoid sensitivities to extreme values. The results are displayed in Table 5.3 along with actual values for 2014 to 2016 to allow comparison, courtesy of the IEA

(2017c). These figures cannot be considered alone as the battery energy capacity of BEVs is far higher than it is for PHEVs. Thus, the percentage of market share for each is also included and extrapolated according to the evident trend until 2030. It is not known how much of the EV market BEV sales will eventually attain, but data for 2017 confirms that 2% per annum is realistic (ev-volumes, 2018).

Table 5.3 Actual sales and market share of EVs (LDV) between 2014 and 2016 with forecasts until 2030.

Year	2014	2015	2016	2020	2025	2030
Sales (million)	0.3	0.6	0.8	4.1	13.2	29.2
BEV Share (%)	58.7	59.5	61.9	70.0	80.0	90.0
PHEV Share (%)	41.3	40.5	38.1	30.0	20.0	10.0

Sources: Data for 2014 to 2016 from the IEA (2017c). Forecasts for sales until 2030 are the median of estimates presented in Table 2.3. Assumptions of market shares are extrapolated from existing trends, after data from the IEA (2017c).

Table 5.4 Summary of EV energy capacity estimates.

Author(s)	Study Year	Energy Capacity (kWh)	
		BEV	PHEV
Gruber *et al.*	2011	28 - 40	9 - 13
Kushnir and Sandén	2012	36	9
Vikstrom *et al.*	2013	25	9
Evans	2014	25	16
Speirs *et al.*	2014	16 - 35	4.3 - 16
Hocking *et al.*	2016	50	25
Berckmans *et al.*	2017	18.2 - 24.2	9
Martin *et al.*	2017	50	5

Source: Various sources are indicated above.

The lithium consumption of this sector is heavily reliant on the energy capacity of BEVs and PHEVs, which varies according to each vehicle model on offer. The various attempts to quantify the typical capacity of each of these technologies is summarized in Table 5.4. These may either be based on surveys of existing vehicles, as in the case of Berckmans *et al.* (2017), or on future customer preferences for longer range vehicles, as Hocking *et al.* (2016) assume. The median for these eight studies is approximately 30 kWh for BEVs and 9 kWh for PHEVs, which will be the assumption for vehicle capacities until 2030. It is difficult to predict if these will change dramatically within the forecasted timeframe of this research, but this could have a large impact on the expected lithium demand.

Only two known published sources discuss the lithium demands of the e-bike sector, although this is backed up by sales figures from the IEA (2017c). A large difference exists between these reports in the estimation of lithium consumption, with Macquarie Research (2016) quoting 4.2 kt LCE in 2021 and Hocking *et al.* (2016) assuming 60.3 kt LCE for the same year. This makes the forecasts of lithium demand for this end market difficult to reconcile. The IEA (2017c) confirms that sales totals will stabilize at present rates of around 25 million e-bikes and 5 million electric three-wheelers, roughly agreeing with estimates from analysts. An average energy capacity of 1 and 6 kWh respectively, with complete Li-ion market penetration by 2025 will be assumed for this research (Hocking *et al.*, 2016; Macquarie Research, 2016).

The application of lithium batteries in grid storage is also a very recent development with only around 1 GWh installed globally in 2016 (US Department of Energy, 2016). Few forecasts are available, all of them attributed to industry analysts and only published within the last couple of years, possibly due to this reason. Predictions are typically provided up until 2025, with only a single source reporting a cumulative amount of new additions between 2017 and 2030, the International Renewable Energy Agency (IRENA) (2017a). These are presented in Table 5.5 along with extrapolations up to 2030 based on previous growth rates of each forecast. Where only cumulative estimates were provided, annual amounts were calculated using a constant growth rate.

While the forecasts for 2020 fall within a relatively close range of between 8.2 and 2.6 GWh, this is compounded by an average 35% growth rate until 2030 leading to a wide range of figures. This reflects the large degree of uncertainty in the growth of this end market and results in some forecasts that are 10 times the estimates of others (BNEF, 2017b; Navigant Research, 2017). Yet, if the median values are calculated, this may represent a justifiable assumption for the purposes of this research. For 2030 specifically, this is a figure of 99.5 GWh in new lithium battery installations for the ESS sector annually.

Table 5.5 Actual and forecasted annual Li-ion ESS Installations.

Source	Study Year	Annual Li-ion ESS Installations (GWh)															
		2015	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
US DoE	2016	0.6	1.0														
Hocking *et al.*	2016			2.0	3.2	6.1	8.2	10.9	15.9	22.7	33.4	48.3	*70.0*	*101.6*	*147.2*	*213.5*	*309.6*
Macquarie Research	2016			2.0	2.7	3.7	5.0	6.7	*9.0*	*12.2*	*16.4*	*22.2*	*30.0*	*40.4*	*54.6*	*73.7*	*99.5*
IRENA	2017			1.3	1.7	2.4	3.2	4.4	6.0	8.3	11.3	15.4	21.1	28.8	39.4	53.9	73.6
BNEF	2017			1.6	2.3	3.5	5.4	8.1	12.2	18.5	27.9	*42.1*	*63.6*	*96.0*	*145.1*	*219.1*	*330.9*
Navigant Research	2017			1.2	1.6	2.0	2.6	3.4	4.5	5.8	7.5	9.8	*12.7*	*16.5*	*21.5*	*27.9*	*36.3*
	Median (GWh)			**1.6**	**2.3**	**3.5**	**5.0**	**6.7**	**9.0**	**12.2**	**16.4**	**22.2**	**30.0**	**40.4**	**54.6**	**73.7**	**99.5**
	Growth Rate (%)		33.3	51.0	51.0	51.0	41.0	34.0	34.9	34.9	34.9	34.9	35.0	35.0	35.0	35.0	35.0

Source: Various sources are indicated above.

Notes:

Actual additions to Li-ion ESS capacity between 2014 and 2016 are provided by the US Department of Energy (US DoE) (2016).

Figures highlighted in red and italicized are extrapolated to 2030 based on the average growth rates of previous estimates.

Figures highlighted in blue are calculated from cumulative additions to Li-ion ESS capacity using a constant growth rate.

Hocking *et al.* (2016) provide forecasts of annual Li-ion ESS installations until 2025.

Macquarie Research (2016) provides forecasts of lithium consumption for the ESS sector until 2021. Their quoted lithium intensity of 0.9 kg LCE per kWh is used to calculate estimates of additions to energy capacity.

IRENA (2017a) predicts that between 181 and 421 GWh will be installed between 2017 and 2030, assuming the renewable share of the market doubles. The average of this estimate is used and adjusted for Li-ion market share, which is assumed to be 90%, after the IEA (2017b).

Bloomberg New Energy Finance (BNEF) (2017b) provides a cumulative estimate of 81 GWh for 2024.

Navigant Research (2017) provides a cumulative estimate of 42.7 GWh for 2025, adjusted for Li-ion market share, which is assumed to be 90%, after the IEA (2017b).

Although not within the realm of this study, all other markets must also be considered when quantifying the total demand for lithium. Analysts from Macquarie Research (2016) and Hocking *et al.* (2016) concur that these are not likely to achieve growth rates beyond the relative growth of the global economy. The demands of the various sectors outside of EVs, ESS and electric bikes were collected from Hocking *et al.* (2016) for 2015 and an annual growth rate of 3% was used to find demands until 2030, presented in Table 5.6.

Table 5.6 Forecasted demand for other end markets (kt LCE, 3% per annum growth rate).

Uses	2015	2020	2025	2030
Other Batteries	48.5	56.2	65.2	75.6
Glass & Ceramics	42.6	49.4	57.3	66.4
Greases	19.0	22.0	25.5	29.6
Air Treatment	7.3	8.5	9.8	11.4
Polymers	6.2	7.2	8.3	9.7
Medical	6.7	7.8	9.0	10.4
Aluminium	2.5	2.9	3.4	3.9
Casting	7.6	8.8	10.2	11.8
Other	15.0	17.4	20.2	23.4
Total (kt LCE)	**155.4**	**180.2**	**208.8**	**242.1**

Source: Data for 2015 from Hocking *et al.* (2016).

In order to tie in estimates for the EV, ESS and e-bike sectors, a figure for the lithium intensity per unit of energy capacity is also required. A detailed discussion of lithium intensity in rechargeable batteries has already been undertaken in section 2.8. It is appropriate that a number of 0.9 kg LCE/kWh is assumed for 2015 in this study, consistent with the higher end of industry estimates (Macquarie Research, 2016). However, material efficiencies should be expected to improve in the future, as observed in the past, due to innovations in both manufacturing and battery chemistries (Kushnir and Sandén, 2012). For this reason, lithium intensity per kWh is assumed to trend towards the lower end of industry estimates of 0.6 kg LCE/kWh by 2030 by way of exponential decay (Hocking *et al.*, 2016). This represents the learning curve also seen in other technologies as discussed by Roberts (1992). For batteries manufactured in the years previous to 2015, the assumed intensity is 1 kg LCE/kWh, corresponding closely to estimates from Kushnir and Sandén (2012).

Potential production from recycling was not included in any of the forecasts seen in Table 5.2, and according to authors, it is not likely to produce any significant amounts of lithium before 2025 (Speirs *et al.*, 2014; Martin *et al.*, 2017). However, if we consider that large capacity batteries have a lifespan of 10 years, and review the additions in EV, ESS and e-bike Li-ion capacity in 2015, we can understand the future availability of recycled lithium. After applying a conservative 80% efficiency rate for recycling and collection, calculations reveal that this would be just shy of 13 kt LCE, approximately 2% of primary production in 2025. This rises rapidly to 77 kt LCE in 2030, or 11% of assumed primary production in 2030, an amount that could prove to be critical in the availability of lithium (Kushnir and Sandén, 2012; Hocking *et al.*, 2016).

Considering that substantial sales of EVs were first seen in 2010 (IEA, 2017c), we may expect that these will become available for recycling early as 2020, although not in significant amounts until 2023. Depleted Li-ion batteries in ESS and e-bike sectors may not become available until at least 2025, though (Hocking *et al.*, 2016). While other smaller capacity batteries may eventually be recycled, it is not known when this will be financially viable or if the lithium contained will be recovered, as it is presently not undertaken in most operations (Sonoc *et al.*, 2015). Thus, this research will not consider the possible contributions of other small capacity batteries to supplies from recycling.

5.3 Synthesis of the Market

The previous assumptions allow for a synthesis of potential market supplies against the demands of applications in the future. This report is most concerned with the material requirements of rechargeable Li-ion batteries in the rapidly emerging markets of EVs and ESS. This is in light of the shift towards cleaner energy consumption driven by the serious concerns of global warming. Current data from the IEA (2017c) and US DoE (2016) show that the sales of EVs and installations of ESS are still very low, but the literature on the topic expects widespread adoption of this technology. Figure 5.1 presents the growth predicted

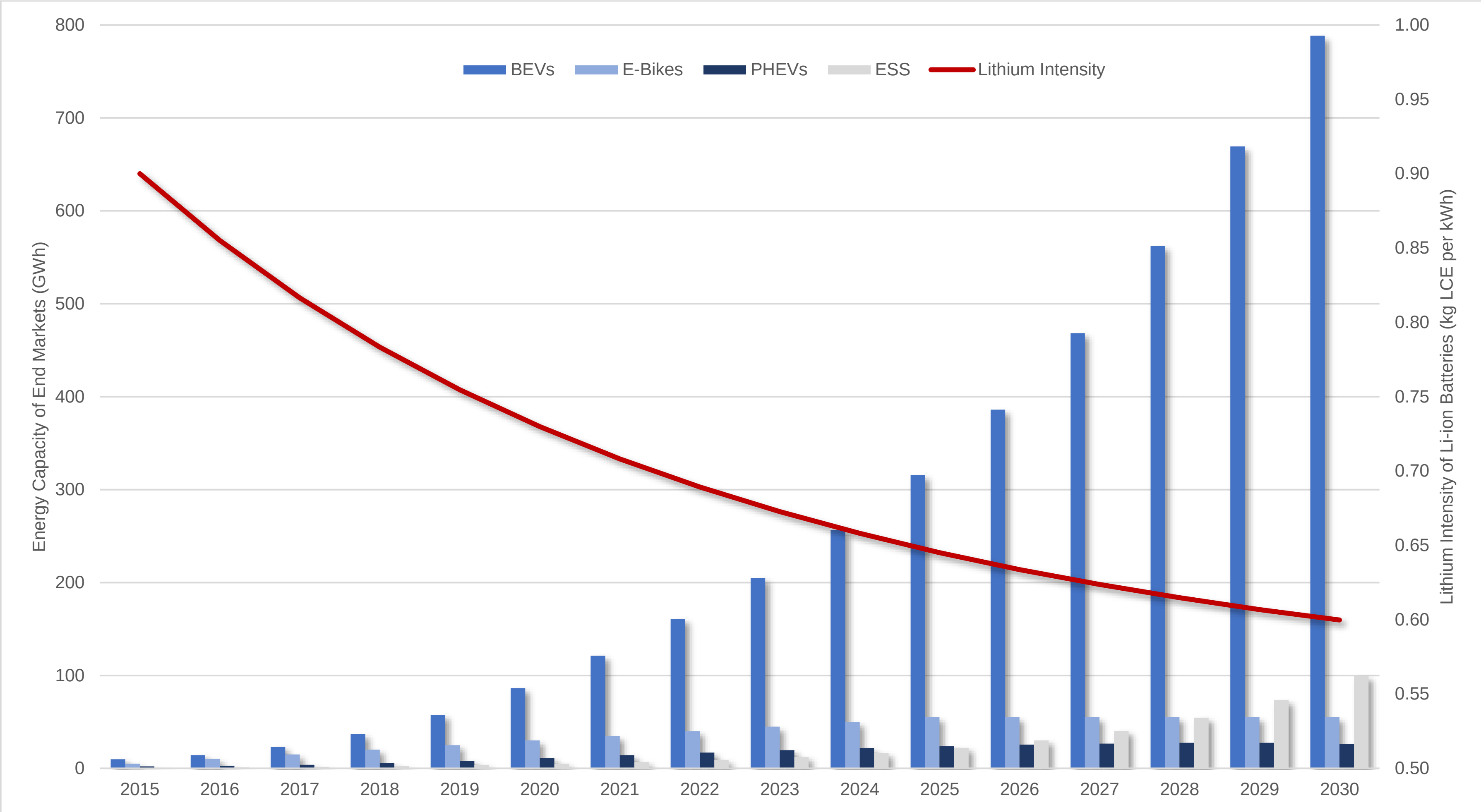

Figure 5.1 Annual additions of energy capacity for each end-market (GWh) versus the lithium intensity of Li-ion batteries (kg LCE/kWh) until 2030.

Notes: The sources and various assumptions that this data is based on is discussed in section 5.2.

between 2015 and 2030 of each of the applications of Li-ion batteries, excluding portable electronics, in terms of annual additions in energy capacity (GWh).

Forecasts for 2030 in the sector of fully electric vehicles (BEVs) alone, dwarfs the size of its market in 2015 by more than 80 times, at 788 GWh. While this is alarming enough, the emergence of applications in ESS appears to be following the same course and may become the second largest market beyond 2030 for lithium. The large capacity of batteries needed for these sectors and the size of their respective markets is behind the predictions and their diffusion is being actively encouraged by governments in the name of lower emissions (Macquarie Research, 2016; IEA, 2017b). The exponential growth observed may be cushioned by improved lithium efficiencies per unit of energy, but these marginal reductions are expected to become more difficult to achieve over time (Figure 5.1).

The growing societal stock of these large capacity batteries illustrates the improving opportunity to recycle lithium over time, especially as earlier iterations should contain a greater share of material per unit of energy. Although, as long as these applications continue to grow or remain stable, recycling will not be able to fully satisfy their demand due to losses in recycling and collection, and dispersive applications (Kushnir and Sandén, 2012). Until this occurs, primary production will need to expand to avoid any shortfalls in supply, which may lead to pricing shocks and the resultant loss of long-term demand through substitution and forced material efficiencies.

The estimation of the lithium requirements of batteries over time allows the calculation of demand for these sectors, in addition to what is expected for traditional uses of lithium. This is displayed in Figure 5.2 along with the predicted supplies from primary production and recycling until 2030. Underlying data for this is presented in Table 5.7 and is based on reports for present quantities as well as the assumptions discussed previously.

While a surplus of extracted lithium is predicted until 2029, market prices have continued to rise until at least the end of 2017 (Shanghai Metals Market, 2017; Jaskula, 2018). This is amidst concerns over tightly controlled supplies, and

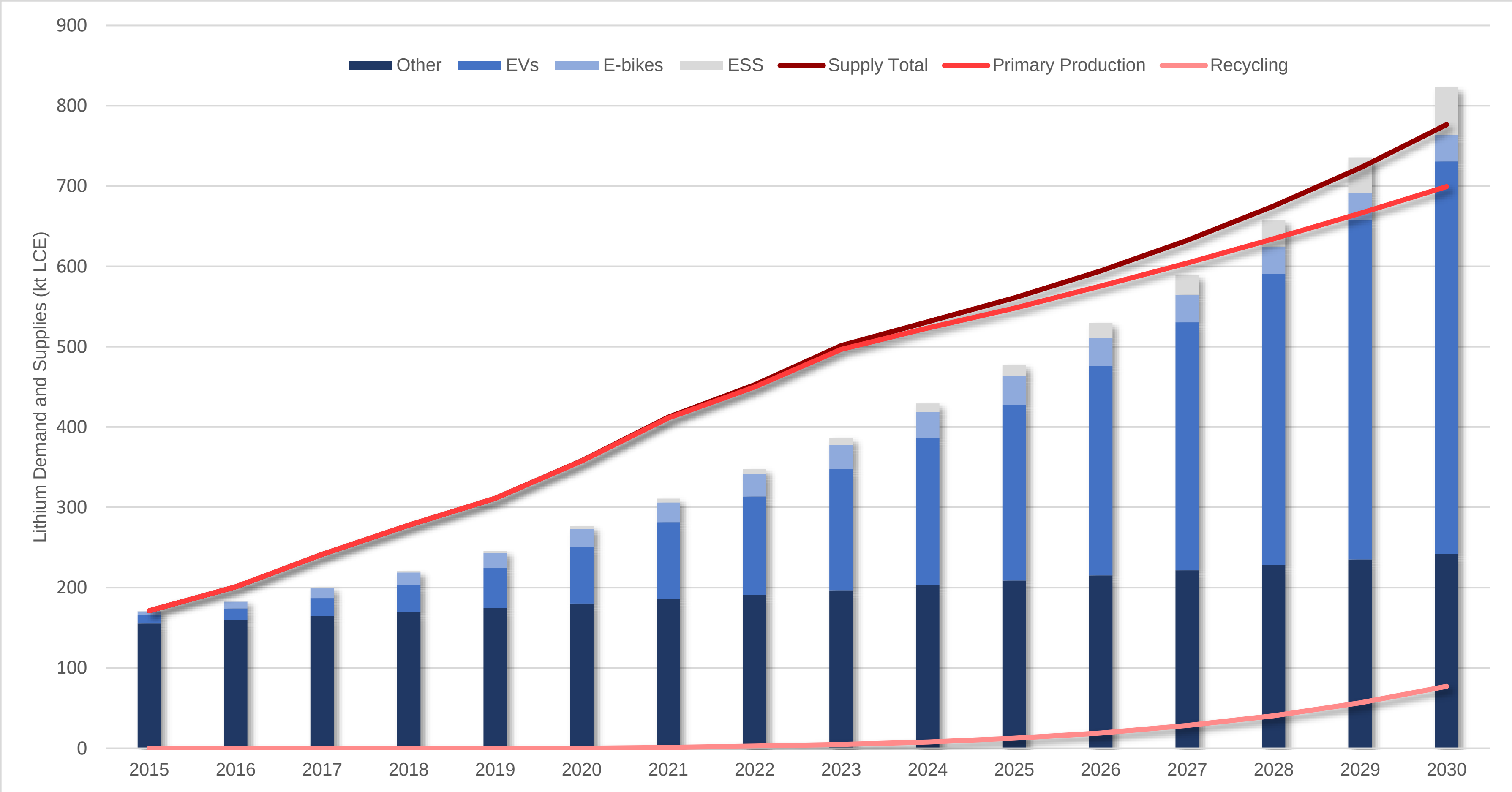

Figure 5.2 Lithium demand of end-markets and supply from primary production and recycling until 2030 (kt LCE).

Notes: The sources and various assumptions that this data is based on is discussed in section 5.2 and displayed in Table 5.7.

Table 5.7 Summary of data for annual lithium supply and demand and the expected market deficit or surplus as a percentage of supplies.

	Supply and End Markets	Units	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Supply	Primary Production	kt LCE	171.2	201.2	241.6	277.8	311.2	357.8	411.2	449.8	496.6	523.4	548.0	575.4	604.2	634.4	666.1	699.4
		growth %		*18%*	*20%*	*15%*	*12%*	*15%*	*15%*	*9%*	*10%*	*5%*	*5%*	*5%*	*5%*	*5%*	*5%*	*5%*
	Recycling	kt LCE	0.0	0.0	0.0	0.0	0.0	0.1	1.2	2.9	4.8	7.7	12.6	18.8	28.4	40.7	56.7	77.2
		% of prim. prod.		*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*1%*	*1%*	*1%*	*2%*	*3%*	*5%*	*6%*	*9%*	*11%*
	Supply Total	kt LCE	**171.2**	**201.2**	**241.6**	**277.8**	**311.2**	**358.0**	**412.4**	**452.7**	**501.4**	**531.1**	**560.6**	**594.3**	**632.6**	**675.0**	**722.8**	**776.6**
		growth %		*18%*	*20%*	*15%*	*12%*	*15%*	*15%*	*10%*	*11%*	*6%*	*6%*	*6%*	*6%*	*7%*	*7%*	*7%*
Demand	Battery Intensity	kg LCE/kWh	0.900	0.855	0.816	0.783	0.755	0.730	0.708	0.689	0.673	0.658	0.645	0.634	0.624	0.615	0.607	0.600
		efficiency %		*-5%*	*-5%*	*-4%*	*-4%*	*-3%*	*-3%*	*-3%*	*-2%*	*-2%*	*-2%*	*-2%*	*-2%*	*-1%*	*-1%*	*-1%*
	EVs	kt LCE	10.6	14.1	22.0	33.3	49.3	70.9	96.0	122.6	150.9	183.1	219.0	260.8	308.8	362.6	422.7	488.7
		growth %		*33%*	*56%*	*51%*	*48%*	*44%*	*35%*	*28%*	*23%*	*21%*	*20%*	*19%*	*18%*	*17%*	*17%*	*16%*
	E-bikes	kt LCE	4.5	8.6	12.2	15.7	18.9	21.9	24.8	27.6	30.3	32.9	35.5	34.9	34.3	33.8	33.4	33.0
		growth %		*90%*	*43%*	*28%*	*20%*	*16%*	*13%*	*11%*	*10%*	*9%*	*8%*	*-2%*	*-2%*	*-1%*	*-1%*	*-1%*
	ESS	kt LCE	0.6	0.9	1.3	1.8	2.7	3.6	4.7	6.2	8.2	10.8	14.3	19.0	25.2	33.6	44.7	59.7
		growth %		*54%*	*44%*	*45%*	*46%*	*36%*	*30%*	*31%*	*32%*	*32%*	*32%*	*33%*	*33%*	*33%*	*33%*	*33%*
	Other	kt LCE	155.4	160.1	164.9	169.8	174.9	180.2	185.6	191.1	196.9	202.8	208.8	215.1	221.6	228.2	235.1	242.1
		growth %		*3%*	*3%*	*3%*	*3%*	*3%*	*3%*	*3%*	*3%*	*3%*	*3%*	*3%*	*3%*	*3%*	*3%*	*3%*
	Demand Total	kt LCE	**171.1**	**183.6**	**200.4**	**220.6**	**245.8**	**276.6**	**311.0**	**347.5**	**386.2**	**429.6**	**477.6**	**529.8**	**589.8**	**658.2**	**735.9**	**823.5**
		growth %		*7%*	*9%*	*10%*	*11%*	*13%*	*12%*	*12%*	*11%*	*11%*	*11%*	*11%*	*11%*	*12%*	*12%*	*12%*
Balance	**Surplus/Deficit**	kt LCE	0.1	17.5	41.2	57.2	65.4	81.4	101.3	105.2	115.2	101.5	83.0	64.5	42.8	16.9	-13.1	-46.9
		% of supply		9%	17%	21%	21%	23%	25%	23%	23%	19%	15%	11%	7%	2%	-2%	-6%

Sources: (Kushnir and Sandén, 2012; Hocking *et al.*, 2016; Macquarie Research, 2016; US Department of Energy, 2016; BNEF, 2017b; IEA, 2017c; IRENA, 2017a; Navigant Research, 2017)

Notes: Details on the sources and various assumptions that this data is based on is discussed in section 5.2.

rapidly growing end-markets of lithium rechargeable batteries (Jaskula, 2018). Many consumers protect themselves from these market surges and ensure availability by entering into long-term bilateral agreements with producers (Macquarie Research, 2016). However, this still incentivizes new stakeholders to start exploration and production, and existing producers to expand operations with the promise of greater profits. This has the positive effect of diversifying the market supply, both in terms of geographic concentration and market players, but it may also result in oversupply.

Several industry commentators predicted or still expect a deflation in prices driven by this market surplus, but a large correction has yet to occur (Hocking *et al.*, 2016; Macquarie Research, 2016; Platts, 2017; Sanderson, 2018). Slightly lower prices in early 2018 may be a sign that this is already happening and even one of the largest producers, SQM, are preparing themselves for declines this year (Els, 2018). Thus, we should consider how stakeholders involved in lithium production may respond to a situation of supply exceeding demand and the resultant lower value of their products.

Tilton and Guzmán (2016) provide an insightful discussion on how the market character, in general, may determine their response, and Kushnir and Sandén (2012) highlight some points more salient to the lithium market. The ability of a few producers to control prices depends on their market share, the price elasticity of demand and the price elasticity of suppliers outside of the cartel or oligopoly (Tilton and Guzmán, 2016). The last point is only relative to the ability of the cartel to respond to price changes and as we have detailed previously, brine extraction of lithium is extremely inelastic. As Macquarie Research (2016) and Ebensperger *et al.* (2005) point out, there is ample evidence that leading producers have strived to curtail their production in an effort to drive lithium prices higher.

While this improves their profit margins, Tilton and Guzmán (2016) highlight that this encourages other market entrants, thus destroying their market share of supply in the long-run. In addition to this, supply concerns cause consumers to find substitutes and improve their material efficiencies, also creating demand destruction. Furthermore, restricting current output reduces the net present value

(NPV) of their operations as money earned today is worth more than the same amount earned at any point in the future (Tilton and Guzmán, 2016).

Kushnir and Sandén (2012) suggest a contrasting situation, where brine producers may flood the market with cheap products forcing all other producers out. The immense size of their reserves would also allow them to do so for a very long time before other deposits may be considered viable. This, of course, also reduces their NPV as they are selling their product for much less than it would be worth in a competitive market environment. It does, however, allow the cartel to regain control of the production market and thus enable price manipulation.

We should circle back to a couple of the factors enabling cartelization; the demand price elasticity and the price elasticity of supply (Tilton and Guzmán, 2016). Lithium demand is highly inelastic due to a lack of adequate substitutes and brine producers require up to two years in lead-time to put a product on the market. Thus, South American production may not be able to reliably expect the exponential rise in lithium demand with sufficient time to react. This leaves mineral producers in the best situation to respond to supply deficits on even a weekly basis. At present, this seems to be how the supply market is behaving with Australia and China ramping up production by around 30% in 2017, while producers in Chile and Argentina scaled back their operations slightly (Jaskula, 2018). It is not likely that this reduced output is due to an inability to respond, however, as demand for lithium has been increasing since 2009 (Evans, 2014).

This is what is expected to occur in the period leading up until 2030. Brine producers should continue to marginally decrease or even increase their output to constrain supplies, although still losing relative market share to mineral producers. This would result in them receiving greater value for fewer quantities of energy spent on production as long as supply does not exceed demand. A smart move, and as Kushnir and Sandén (2012) note, even to be expected of a situation such as this. However, as supply overruns are forecasted until 2029 (Figure 5.2), it must be stated this estimated production should only be viewed as the capacity of producers to extract lithium. The inclination of producers to operate at full capacity is a very different matter and is underpinned by the size of the demand market.

Mineral operations, such as those in Australia, should produce enough to fill the expected supply gap between what brine producers are allowing onto the market and what demand is predicted to be. In fact, they have sufficient price incentive to continue to produce until their marginal costs equal market value, which is much higher than the typical costs of mineral extraction at present (Evans, 2014; Jacobs, 2018). However, this is only what producers are expected to do in a perfectly competitive market (Tilton and Guzmán, 2016).

Although the price incentive is high enough for a mineral producer, such as Talison Lithium, to continue to produce beyond this, they will not be able to find willing buyers beyond this quantity for the same market value. Thus, they could either:

1. sell any excess product onto the market at cheaper prices,
2. scale back the output of their operations, or
3. stockpile any surplus lithium produced.

The first option would destroy the value of their future operations as this causes lithium prices to deflate. The latter two options should not negatively impact prices, but the last would delay reimbursement for costs of production and accrue debt until it is sold. This would only be practical if the price of lithium is expected to increase. Nevertheless, it is predicted that while Talison Lithium maintains market dominance in lithium mineral extraction, supply should not significantly deviate from forecasted demand until 2029. This would be achieved by curtailing their possible capacity enough so that demand is met without price destruction. In the long-run though, this would still allow other operations to expand at a rate equal to their ability to respond, eventually bringing prices lower than what they are at present.

Based on the assumption that large capacity batteries would prove feasible enough to recycle, production from secondary operations would produce an amount equal to 1% of primary production in 2023 (Table 5.7). This is due to the number of EV sales in 2013 when assuming a 10-year design life and an 80% recycling efficiency (Kushnir and Sandén, 2012; IEA, 2017c). With the exponential growth of this sector in addition to further applications in ESS and e-bikes, this is forecast to increase to 11% by the year 2030. Recycling would still not be sufficient enough to plug the growing supply deficit in the years 2029 and 2030, as demand is expected to grow quicker than total supplies.

Thus, if primary producers are not able to expand the capacity of existing operations or if new greenfield projects cannot fulfil this growth in demand, a price surge should be expected in 2029 and beyond. This has been observed in many other mineral markets where production cannot meet the demand for various reasons. Even an improvement in recycling efficiencies and collection would not significantly affect the availability of supplies, as most of the societal stock of large capacity Li-ion batteries would not have reached the end of their intended life.

5.4 Limitations and Risks to Findings

There are however several risks to the deductions of this research in addition to other factors that are impossible to predict at this point. Specific to emerging markets of EVs and ESS, it is difficult to state with certainty how quickly these applications will grow. Large variations in forecasts amongst published works on the subject are evidence of this. This is especially true for ESS, which has only seen the adoption of Li-ion in the last few years. There are also sub-sectors within the EV market such as trucks and buses, which are expected to use this technology in the future but do not do so in significant numbers at present. These would require much higher capacity batteries and would, therefore, require large amounts of lithium not accounted for in this study.

Compounding this issue is the expected requirements of lithium per kWh. While assumptions were made upon the best industry estimates, battery manufacturers do not make this information publicly available. New innovations in battery chemistry such as $Li\text{-}O_2$ or Li-S could also drastically improve energy capacities, thus vastly improving material efficiency. In the same manner, other battery chemistries could eliminate the need for lithium in this application, although the consensus amongst authors is that this is not likely in the near future. Substitution could also take place at a higher level if new engineering solutions are found to be more practical than electrochemical energy storage. An example of this may be hydrogen storage in the ESS sector but this is yet to be shown to be effective.

Demand for these batteries is driven by global trends and economic growth such as emission reduction policies, urbanisation, population growth and productivity. If any of these factors deviate from what is reasonably expected, this could have the greatest possible impact on the diffusion of Li-ion technology. The recession in 2008, for instance, led to reductions in lithium production, vehicles sales, electricity generation as well as carbon-dioxide emissions (Evans, 2014; OICA, 2017; Enerdata, 2018). Disruptions in these trends are almost impossible to forecast and thus cannot be accounted for. There are also emerging consumer preferences for vehicle automation and ride-sharing or hailing that may eventually reduce the effective size of the market for EVs by lowering rates of vehicle ownership (Chan, 2017). These are still recent, and like electric buses and trucks, make it difficult to estimate.

Regarding security of supplies, the concern of concentration of producers and reserves is a very valid threat. This could come from governments restricting the capacities of producers or enforcing unreasonable export duties, or from more incidental cases such as war or mining accidents. Risks also lie in the producer control of the market, and although this has not occurred yet, corporate strategies may change and alter the current dynamic. The greatest possibility of supply constraints may be in the availability of other Li-ion battery materials. Cobalt is a large and necessary constituent of the highest performing iterations of this technology and any disruption in its primary production could lead to market shocks that severely impact battery manufacturing (Larcher and Tarascon, 2015; Macquarie Research, 2016).

As Maxwell (2015) proposes, a structural change in the way that lithium is marketed could also introduce other risks and may occur before 2025. Listing of a commodity on an exchange introduces the ability of investors to speculate, which is often cited as a major cause of price volatility. Although there are also benefits to this mechanism, such as a more open and competitive market, it cannot be reliably forecasted how this might affect lithium prices specifically.

While an effort to estimate how much lithium could be recovered by recycling in the future, there are a few problems with this as well. The design-life of batteries could be much greater than it is at present and it is suggested that they could be re-used in other applications, furthering their technical life (Diouf and Pode, 2015). This would remove them from being available for processing and, thus, very little supply could realistically be expected from recycling before 2030 if this occurs. Taking a more optimistic view, Hocking *et al.* (2016) predicted 65 kt LCE to be used annually in other uses of lithium batteries in 2025. These generally possess much smaller capacities but if they were to be included in recycling for 2030, due to their shorter lifespan, this could make up for the supply deficit alone.

There may be many uncertainties regarding the widespread adoption of Li-ion technology, supply rates and the markets that they are applied in. This research aims to assess these market dynamics using only the most balanced forecasts and assumptions, but risks and limitations will persist. These should be taken into consideration when understanding the findings of this study.

6 CONCLUSIONS AND RECOMMENDATIONS

The last decade has seen large-scale installations of renewable energy generation and ever-increasing sales of EVs. This has been enabled by the advancing potential of the Li-ion battery to store large amounts of energy in a compact form and deliver it far more efficiently than many of its competitors. Even though it was initially only designed for portable electronics, it is finding widespread adoption in vehicles, which is, in turn, spurring market penetration into energy storage applications.

The concern with the rapid diffusion of Li-ion technology in EVs and ESS is whether the production capacity and resources of lithium are sufficient to meet demands in the future. This requires an analysis of not only supplies but also an assessment of the growth of the emerging markets where rechargeable lithium batteries are being used. Complicating the issue are the factors of competing technologies, possible material substitutions and improvements in manufacturing efficiencies. Also, in question is the opportunity to recycle or reuse societal stocks of lithium to support these new markets. This research aims to balance and forecast these factors and understand how markets may respond.

Sales of EVs are still relatively insignificant, around 750 thousand when compared to the 90 million conventional LDVs manufactured in 2016. However, it has grown by an average of 77% since 2012 and they require up to 27 kg LCE for each vehicle. This points to a massive potential material requirement in the coming decades if they continue to penetrate the market as they have done. The study found that 522 kt LCE may be needed to supply the EV and e-bike sectors alone by 2030, over three times the lithium produced in 2015. This does not consider the emergence of applications in higher capacity vehicles such as buses and trucks, however. New consumer preferences in vehicle automation, ride-sharing and hailing could reduce per capita vehicle ownership but this is yet to be shown.

Research and innovation in the EV sector have provided inroads for Li-ion batteries into ESS by improving performance, safety and cost. This technology has many competitors in this market, but it is proving to be the most popular in the categories of bridging power and small to medium-scale energy management (100 kW to 100 MW). The driving factor in this trend is the large-scale installations of intermittent renewable energy that require ESS to make them dependable sources. Renewable power generation comprised a quarter of the global total in 2016 and Li-ion batteries accounted for 90% of non-PHS and TES grid storage additions in the same year. Uncertainties are significant for the year 2030, but the information suggests that 60 kt LCE will be required in these systems, growing exponentially thereafter. The rising lithium demand for this application may be buffered by either EV battery re-use or vehicle-to-grid technology, though.

Global accords such as the Paris Agreement appear to be the reason behind the shift to clean energy, but it is also due to a growing awareness of our impact on the environment. As such, governments are actively encouraging the adoption of EVs, renewable energy and ESS through policies. This is a positive development considering that the world requires an estimated 50% more energy output by 2050. These changes, though, are placing an undue amount of strain on mineral resources needed in the technology supporting cleaner energy, Li-ion. Greater accountability of consumers of metals is needed while understanding the impacts of mineral production and its contribution to a carbon-reduced economy.

All technologies face the risk of substitution, but lithium batteries' superior energy density, efficiency and lifetime have won it the majority share of the market in EVs. This is expected to continue until at least to 2030 and may be secured in the long-term by new innovations in chemistry. In ESS, the future is not so certain due to flow batteries and mechanical solutions, such as PHS and TES. Eventually, the market will decide the most appropriate solution, but for now, Li-ion seems to be taking a large stake. Material efficiencies in manufacturing have been observed in the past, and are expected to continue, albeit at a slower rate, to around 600 g LCE/kWh by 2030. Drastic improvements could occur in the form of Li-S and Li-O_2 batteries if they are proved to be successful, however, this is still years away.

On the supply side of the market, production is viewed to be in over-capacity until 2029 and there is no physical shortage of lithium reserves for at least the next 50 years. Of greater concern, though, is the economic availability of lithium due to the severe concentration of producers and the reserves they operate on. Operations are already limiting their extraction rates to support market prices and brine production is highly vulnerable to disruption due to lead times of around two years. The five dominant producers should be expected to exert market control by paring back their potential capacities in the next decade. Mineral production of lithium in Australia and China is predicted to expand the most due to their ability to react quickly to demand.

New greenfield operations and improvement of capacity at existing operations will be required by 2029 and beyond. A failure to do so will result in disruptions that may put rechargeable lithium battery technology at risk of being priced out of the market and destroying its potential. This may occur even earlier than this in other markets relating to Li-ion technology. Cobalt is most at risk due to its even greater geographic concentration of production. Recent examples have already been observed in PGM and REE markets and should be avoided. Further research into alternative anodes should, therefore, be treated as a matter of urgency to remove the dependency on these materials.

Recycling may be the most critical and effective means of diversifying and improving supplies. This could provide an amount equal to 11% of primary production by the end of the period observed. Yet, governments need to focus on improved policies and institutional support if this is to occur. Currently, less than a percent of societal lithium is recycled as collection strategies are insufficient and secondary extraction is deemed uneconomic. The importance of recycling should also be recognized for its contribution to reduced emissions. Consumers and manufacturers should be made aware of this and encouraged to recycle through incentivisation and legislation.

The balance of supply and demand ultimately determines the market price, but it may in turn impact upon production, recycling and reserves, as well as consumer demand for this technology. High commodity prices, for example, motivate new producers and expand the base of economically viable reserves, while reducing the cost-competitiveness of this technology. This is the delicate dynamic in the lithium market that is at risk of collapse if it is put out of kilter. Demand for practical energy storage is unrelenting so a fine equilibrium between improving supplies and an acceptable market price will need to be struck. This will ensure the viability of Li-ion batteries in the future, which is tied strongly to a cleaner global economy.

7 REFERENCES

Abada, S., Marlair, G., Lecocq, A., Petit, M., Sauvant-Moynot, V. and Huet, F., 2016. Safety focused modeling of lithium-ion batteries: A review, *Journal of Power Sources*. Elsevier B.V, vol. 306, pp. 178–192.

Anderson, C. S., 2016. *Selenium and Tellurium*. Reston, USA. Available at: https://minerals.usgs.gov/minerals/pubs/commodity/selenium/myb1-2012-selen.pdf.

Andersson, B. A. and Råde, I., 2001. Metal resource constraints of electric-vehicle batteries, *Transportation Research Part D: Transport and Environment*, vol. 6, no. 5, pp. 297–324.

Arezki, R., Hadri, K., Loungani, P. and Rao, Y., 2014. Testing the Prebisch-Singer hypothesis since 1650: Evidence from panel techniques that allow for multiple breaks, *Journal of International Money and Finance*. Elsevier Ltd, vol. 42, pp. 208–223.

Asian Metal, 2018. *Lithium*, *http://www.asianmetal.com*. Available at: http://www.asianmetal.com/LithiumPrice/Lithium.html (accessed: February 2018).

Bansal, P., 2015. Charging of Electric Vehicles: Technology and Policy Implications, *Journal of Science Policy & Governance*, vol. 6, no. 1, pp. 1–20.

Bardi, U., 2010. Extracting minerals from seawater: An energy analysis, *Sustainability*, vol. 2, no. 4, pp. 980–992.

Baylis, R., 2013. Evaluating and forecasting the lithium market from a value perspective, in *5th Lithium Supply & Markets*. www.indmin.com, London, United Kingdom, pp. 1–29. Available at: http://www.indmin.com/events/download.ashx/document/speaker/6566/a0ID000000X0jbjMAB/Presentation.

Berckmans, G., Messagie, M., Smekens, J., Omar, N., Vanhaverbeke, L. and Van Mierlo, J., 2017. Cost Projection of State of the Art Lithium-Ion Batteries for Electric Vehicles Up to 2030, *Energies*, vol. 10, no. 9, pp. 1–20.

Berret, M., Mogge, F., Schlick, T., Fellhauer, E., Söndermann, C. and Schmidt, M., 2016. *Global automotive supplier study 2013*, *Lazard & RolandBerger*. Available at: https://www.rolandberger.com/en/press/Automotive-Suppliers-2016.html.

Le Billon, P. and Good, E., 2016. Responding to the commodity bust: Downturns, policies and poverty in extractive sector dependent countries, *Extractive Industries and Society*. Elsevier Ltd., vol. 3, no. 1, pp. 204–216.

Blomgren, G. E., 2017. The Development and Future of Lithium Ion Batteries, *Journal of The Electrochemical Society*, vol. 164, no. 1, pp. A5019–A5025.

BMW, 2017. *BMW i3 warranty and mobile care handbook*. Sheffield. Available at: https://www.bmw.co.uk/dam/brandBM/marketGB/countryGB/newvehicles/i-series/i3/bmwi-aftersales/BMW-i3-Warranty-Handbook.PDF.

BNEF, 2017a. *Electric vehicle outlook 2017*. New York, USA. Available at: https://data.bloomberglp.com/bnef/sites/14/2017/07/BNEF_EVO_2017_ExecutiveSummary.pdf.

BNEF, 2017b. *Lithium-ion Battery Costs and Market*. New York. Available at: https://data.bloomberglp.com/bnef/sites/14/2017/07/BNEF-Lithium-ion-battery-costs-and-market.pdf.

Boggia, P., 2015. *Global Passenger Car Powertrain and Electric Vehicle Market: 2015 Outlook*. UK International Press, London, United Kingdom. Available at: http://www.ukintpress-conferences.com/uploads/SPKEX15/Day1_4_Pietro_Boggia.pdf.

Brown, D. and Chvala, W., 2003. Flywheel Energy Storage: An alternative to batteries for UPS Systems, *Energy Engineering*, vol. 102, no. 5, pp. 1–17.

Brown, T., Walters, A., Idoine, N., Gunn, G., Shaw, R. A. and Rayner, D., 2016. *Lithium*, *Mineral Profile*. Keyworth, United Kingdom. Available at: https://www.bgs.ac.uk/downloads/start.cfm?id=3100.

Bruce, P. G., Freunberger, S. A., Hardwick, L. J. and Tarascon, J.-M., 2011. Li–O2 and Li–S batteries with high energy storage, *Nature Materials*, vol. 11, no.

02, pp. 19–29.

Buchmann, I., 2017. *Types of Battery Cells*, *Battery University*. Available at: http://batteryuniversity.com/learn/article/types_of_battery_cells (accessed: November 2017).

Button, K., Ngoe, N. and Hine, J., 1993. Modelling Vehicle Ownership and Use in Low Income Countries, *Journal of Transport Economics and Policy*, vol. 27, no. 1, pp. 51–67.

Cairns, R. D., 1984. Changing structure in the world nickel industry, *Antitrust Bulletin*. HeinOnline, vol. 29, pp. 1–561.

Castilla, J., 2017. *Argentina seeks to overtake Chile in South America lithium race*, *www.reuters.com*. Available at: https://www.reuters.com/article/argentina-mining-lithium/corrected-feature-argentina-seeks-to-overtake-chile-in-south-america-lithium-race-idUSL8N1NJ6XJ (accessed: January 2018).

Chan, C.-Y., 2017. Advancements, prospects, and impacts of automated driving systems, *International Journal of Transportation Science and Technology*. Tongji University and Tongji University Press, vol. 6, no. 3, pp. 208–216.

Choubey, P. K., Chung, K. S., Kim, M. S., Lee, J. C. and Srivastava, R. R., 2017. Advance review on the exploitation of the prominent energy-storage element Lithium. Part II: From sea water and spent lithium ion batteries (LIBs), *Minerals Engineering*. Elsevier, vol. 110, no. January 2017, pp. 104–121.

Ciez, R. E. and Whitacre, J. F., 2016. The cost of lithium is unlikely to upend the price of Li-ion storage systems, *Journal of Power Sources*. Elsevier B.V, vol. 320, pp. 310–313. Available at: http://dx.doi.org/10.1016/j.jpowsour.2016.04.073.

Cole, D., 2015. *The Global Uranium Ore Market*. Available at: http://www.business.uwa.edu.au/__data/assets/pdf_file/0007/2843251/Duke-Cole-THE-GLOBAL-URANIUM-MARKET.pdf.

Cox, P. M., Betts, R. A., Jones, C. D., Spall, S. A. and Totterdell, I. J., 2000. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model, *Nature*, vol. 408, no. 6813, pp. 184–187.

Creation Inn, 2017. *Recycled lithium to reach 9 percent of total lithium battery supply in 2025*, *Creation Inn*. Available at: https://www.creationinn.com/news/2017/11/30/press-release-recycled-lithium-to-reach-9-percent-of-total-lithium-battery-supply-in-2025 (accessed: February 2018).

Dargay, J., Gately, D. and Sommer, M., 2007. Vehicle Ownership and Income Growth, Worldwide : 1960-2030, *The Energy Journal*, vol. 28, no. 4, pp. 143–170.

Deloitte, 2015. *Electricity Storage Technologies, Impacts, and Prospects*. Available at: https://www2.deloitte.com/content/dam/Deloitte/us/Documents/energy-resources/us-er-electric-storage-paper.pdf.

Díaz-González, F., Sumper, A., Gomis-Bellmunt, O. and Villafáfila-Robles, R., 2012. A review of energy storage technologies for wind power applications, *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, vol. 16, no. 4, pp. 2154–2171.

Diaz de la Rubia, T., Klein, F., Shaffer, B., Kim, N. and Lovric, G., 2015. *Energy storage: Tracking the technologies that will transform the power sector*, *Deloitte*. Available at: https://www2.deloitte.com/content/dam/Deloitte/us/Documents/energy-resources/us-er-energy-storage-tracking-technologies-transform-power-sector.pdf.

Diouf, B. and Pode, R., 2015. Potential of lithium-ion batteries in renewable energy, *Renewable Energy*. Elsevier Ltd, vol. 76, pp. 375–380.

Du, X. and Graedel, T. E., 2013. Uncovering the end uses of the rare earth elements, *Science of the Total Environment*. Elsevier B.V., vol. 461–462, pp. 781–784.

Dunn, B., Kamath, H. and Tarascon, J.-M., 2011. Electrical Energy Storage for the Grid-A Battery of Choices, *Science*, vol. 334, no. 6058, pp. 928–935.

Ebensperger, A., Maxwell, P. and Moscoso, C., 2005. The lithium industry: Its recent evolution and future prospects, *Resources Policy*, vol. 30, no. 3, pp. 218–231.

Ellis, T. and Mirza, A., 2014. Battery Recycling: defining the market and identifying the technology required to keep high value materials in the economy and out of the waste dump, *www.researchgate.net*, , no. February 2015, pp. 1–33. Available at: http://www.nist.gov/tip/wp/pswp/upload/245_battery_recycling_defining_the_market.pdf.

Els, F., 2018. *Rush for cobalt, lithium as prices stay on the boil*, *www.mining.com*. Available at: http://www.mining.com/rush-cobalt-lithium-prices-stay-boil/ (accessed: March 2018).

Enerdata, 2018. *World Energy Statistical Yearbook 2017*, *Enerdata*. Available at: https://yearbook.enerdata.net/ (accessed: January 2018).

European Commission, 2013. *Directive 2006/66/Ec of the European Parliament and of the Council*. Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02006L0066-20131230&rid=1.

ev-volumes, 2018. *The Electric Vehicle World Sales Database*, *www.ev-volumes.com*. Available at: http://www.ev-volumes.com/country/total-world-plug-in-vehicle-volumes/ (accessed: March 2018).

Evans, K., 2014. Lithium, in Gunn, G. (ed.) *Critical Metals Handbook*. 1st edn. John Wiley & Sons, Ltd, San Diego, pp. 230–261.

Evans, R. K., 1978. Lithium reserves and resources, in *Lithium Needs and Resources*. Elsevier, pp. 379–385.

Evans, R. K., 2008. *An abundance of Lithium*. Available at: http://www.evworld.com/library/KEvans_LithiumAbunance_pt2.pdf.

Evans, R. K., 2010. The lithium-brine reserve conundrum, *Northern Miner*, vol.

96, no. 35, pp. 2–6.

Farley, J. and Costanza, R., 2002. Envisioning shared goals for humanity: A detailed, shared vision of a sustainable and desirable USA in 2100, *Ecological Economics*, vol. 43, no. 2–3, pp. 245–259.

Fasel, D. and Tran, M. Q., 2005. Availability of lithium in the context of future D-T fusion reactors, *Fusion Engineering and Design*, vol. 75–79, pp. 1163–1168.

Federal Aviation Administration, 2017. *Lithium batteries & lithium powered devices*. Available at: https://www.faa.gov/about/office_org/headquarters_offices/ash/ash_programs/hazmat/aircarrier_info/media/battery_incident_chart.pdf.

Gaines, L., 2014. The future of automotive lithium-ion battery recycling: Charting a sustainable course, *Sustainable Materials and Technologies*. Elsevier B.V., vol. 1, pp. 2–7.

Gao, P., Kaas, H., Mohr, D. and Wee, D., 2016. *Disruptive trends that will transform the auto industry*, *www.mckinsey.com*. Available at: https://www.mckinsey.com/industries/high-tech/our-insights/disruptive-trends-that-will-transform-the-auto-industry (accessed: December 2017).

Garrett, D. E., 2004. *Handbook of lithium and natural calcium chloride*. Academic Press.

Georgi-Maschler, T., Friedrich, B., Weyhe, R., Heegn, H. and Rutz, M., 2012. Development of a recycling process for Li-ion batteries, *Journal of Power Sources*. Elsevier B.V., vol. 207, pp. 173–182.

Geyer, R. and Blass, V. D., 2010. The economics of cell phone reuse and recycling, *International Journal of Advanced Manufacturing Technology*, vol. 47, no. 5–8, pp. 515–525.

Graedel, T. E., Barr, R., Cordier, D., Enriquez, M., Hagelüken, C., Hammond, N. G., Kesler, S., Mudd, G., Nassar, N., Peacey, J. *et al.*, 2011. *Estimating long-run geological stocks of metals*, *UNEP International Panel on Sustainable Resource Management*. Paris, France.

Grandell, L., Lehtilä, A., Kivinen, M., Koljonen, T., Kihlman, S. and Lauri, L. S., 2016. Role of critical metals in the future markets of clean energy technologies, *Renewable Energy*, vol. 95, pp. 53–62.

Gratz, E., Sa, Q., Apelian, D. and Wang, Y., 2014. A closed loop process for recycling spent lithium ion batteries, *Journal of Power Sources*. Elsevier B.V, vol. 262, pp. 255–262.

Grosjean, C., Miranda, P. H., Perrin, M. and Poggi, P., 2012. Assessment of world lithium resources and consequences of their geographic distribution on the expected development of the electric vehicle industry, *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, vol. 16, no. 3, pp. 1735–1744.

Grossman, G. M. and Krueger, A. B., 1991. *Environmental impacts of a North American free trade agreement*. Available at: http://www.nber.org/papers/w3914.pdf.

Gruber, P. W., Medina, P. A., Keoleian, G. A., Kesler, S. E., Everson, M. P. and Wallington, T. J., 2011. Global lithium availability: A constraint for electric vehicles?, *Journal of Industrial Ecology*, vol. 15, no. 5, pp. 760–775.

Guzmán, J. I., Nishiyama, T. and Tilton, J. E., 2005. Trends in the intensity of copper use in Japan since 1960, *Resources Policy*, vol. 30, no. 1, pp. 21–27.

Habib, K., 2015. *Critical Resources in Clean Energy Technologies and Waste Flows*. University of Southern Denmark. Available at: http://findresearcher.sdu.dk/portal/files/116675109/PhD_thesis_Komal_Habib.pdf.

Habib, K., Hamelin, L. and Wenzel, H., 2016. A dynamic perspective of the geopolitical supply risk of metals, *Journal of Cleaner Production*. Elsevier Ltd, vol. 133, pp. 850–858.

Habib, K. and Wenzel, H., 2014. Exploring rare earths supply constraints for the emerging clean energy technologies and the role of recycling, *Journal of Cleaner Production*. Elsevier Ltd, vol. 84, no. 1, pp. 348–359.

Hall, D., Moultak, M. and Lutsey, N., 2017. *Electric vehicle capitals of the world:*

Demonstrating the path to electric drive, *The International Council on Clean Transportation*. Available at: https://www.theicct.org/sites/default/files/publications/Global-EV-Capitals_White-Paper_06032017_vF.pdf.

Hao, H., Liu, Z., Zhao, F., Geng, Y. and Sarkis, J., 2017. Material flow analysis of lithium in China, *Resources Policy*, vol. 51, no. November 2016, pp. 100–106.

Hao, H., Geng, Y. and Sarkis, J., 2016. Carbon footprint of global passenger cars: Scenarios through 2050, *Energy*. Elsevier Ltd, vol. 101, pp. 121–131.

Hao, H., Wang, H. and Yi, R., 2011. Hybrid modeling of China's vehicle ownership and projection through 2050, *Energy*. Elsevier Ltd, vol. 36, no. 2, pp. 1351–1361.

Hart, W. A., Beumel, O. F. and Whaley, T. P., 1973. Lithium and its compounds, in Hart, W., Beumel, O., and Whaley, T. (eds) *The chemistry of lithium, sodium, potassium, rubidium, cesium and francium: pergamon texts in inorganic chemistry*. 2nd edn. Pergamon Press, pp. 331–367.

Harvey, J., 2017. *Metal recyclers prepare for electric car revolution*, *Reuters*. Available at: https://www.reuters.com/article/us-batteries-recycling-analysis/metal-recyclers-prepare-for-electric-car-revolution-idUSKBN1DH1DS (accessed: February 2018).

Hawksworth, J., Audino, H. and Clarry, R., 2017. *The Long View: How will the global economic order change by 2050?* London, United Kingdom. Available at: http://www.pwc.com/gx/en/world-2050/assets/pwc-the-world-in-2050-full-report-feb-2017.pdf.

Heelan, J., Gratz, E., Zheng, Z., Wang, Q., Chen, M., Apelian, D. and Wang, Y., 2016. Current and Prospective Li-Ion Battery Recycling and Recovery Processes, *The Minerals, Metals & Materials Society*, vol. 68, no. 10, pp. 2632–2638.

Hein, R., Kleindorfer, P. R. and Spinler, S., 2012. Valuation of electric vehicle batteries in vehicle-to-grid and battery-to-grid systems, *Technological Forecasting and Social Change*. Elsevier Inc., vol. 79, no. 9, pp. 1654–1671.

Henckens, M. L. C. M., van Ierland, E. C., Driessen, P. P. J. and Worrell, E., 2016. Mineral resources: Geological scarcity, market price trends, and future generations, *Resources Policy*. Elsevier, vol. 49, pp. 102–111.

Henckens, M. L. C. M., Driessen, P. P. J. and Worrell, E., 2014. Metal scarcity and sustainability, analyzing the necessity to reduce the extraction of scarce metals, *Resources, Conservation and Recycling*. Elsevier B.V., vol. 93, pp. 1–8.

Hocking, M., Kan, J., Young, P., Terry, C. and Begleiter, D., 2016. *Lithium 101*. Sydney, Australia. Available at: http://www.belmontresources.com/LithiumReport.pdf.

Hops, N., 2016. *Disruption in the automotive industry*. Johannesburg, South Africa. Available at: http://www.investonline.co.za/wp-content/uploads/2013/06/Disruption-in-the-automotive-industry-by-Nicholas-Hops.pdf.

Humphries, M., 2012. *Rare Earth Elements: The Global Supply Chain*, *www.crs.gov*. Available at: http://www.fas.org/sgp/crs/natsec/R41347.pdf.

Ide, F. and Kunasz, I. A., 1989. Origin of lithium in Salar de Atacama, northern Chile, in Ericksen, G. E., Canas Pinochet, M. T., and Reinemund, J. A. (eds) *Geology of the Andes and Its Relation to Hydrocarbon and Mineral Resources*. Circum-Pacific Council for Energy and Mineral Resources, Houston, Texas, pp. 165–172.

IEA, 2010. *Power Generation from Coal: Measuring and Reporting Efficiency Performance and CO2 Emissions*, *www.iea.org*. Paris, France. Available at: https://www.iea.org/ciab/papers/power_generation_from_coal.pdf.

IEA, 2011. *Technology roadmap: Electric and plug-in hybrid electric vehicles*, *www.iea.org*. Paris, France. Available at: http://www.iea.org/publications/freepublications/publication/technology-roadmap-electric-and-plug-in-hybrid-electric-vehicles-evphev.html.

IEA, 2017a. *CO2 emissions from fuel combustion*, *www.iea.org*. Paris, France. Available at: http://www.iea.org/publications/freepublications/publication/CO2EmissionsFromFuelCombustion2017Overview.pdf.

IEA, 2017b. *Energy Technology Perspectives 2017*, *www.iea.org*. Paris, France. Available at: http://www.oecd-ilibrary.org/energy/energy-technology-perspectives-2017_energy_tech-2017-en.

IEA, 2017c. *Global EV Outlook 2017: Two million and counting*, *www.iea.org*. Paris, France. Available at: https://www.iea.org/publications/freepublications/publication/GlobalEVOutlook2017.pdf.

IEA, 2017d. *Key World Energy Statistics*, *www.iea.org*. Paris, France. Available at: https://www.iea.org/publications/freepublications/publication/KeyWorld2017.pdf.

IEA, 2017e. *Market Report Series: Renewables 2017*, *www.iea.org*. Paris, France. Available at: http://www.iea.org/bookshop/.

IEC, 2011. *Electrical Energy Storage - White Paper*, *International Electrotechnical Commission*. Geneva, Switzerland. Available at: http://www.iec.ch/whitepaper/pdf/iecWP-energystorage-LR-en.pdf.

Industrial Minerals, 2018. *Lithium*, *http://www.indmin.com*. Available at: http://www.indmin.com/Lithium.html (accessed: February 2018).

IPCC, 2014. *Climate Change 2014*, *IPCC*. Available at: https://www.ipcc.ch/pdf/assessment-report/ar5/wg3/WGIIIAR5_SPM_TS_Volume.pdf.

IRENA, 2017a. *Electricity Storage and Renewables : Costs and Markets To 2030*, *www.irena.org*. Abu Dhabi. Available at: http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf.

IRENA, 2017b. *REthinking Energy*, *www.irena.org*. Abu Dhabi. Available at:

http://www.irena.org/DocumentDownloads/Publications/IRENA_REthinking_Energy_2017.pdf.

Jackson, T. and Green, K. P., 2017. Annual Survey of Mining Companies 2016, *Fraser Institute*, , no. February, pp. 1–74. Available at: https://www.fraserinstitute.org/sites/default/files/survey-of-mining-companies-2016.pdf.

Jacobs, J., 2018. *Benchmark: What Drove Lithium Prices in December? – Global X Funds*, *Global X Funds*. Available at: https://www.globalxfunds.com/benchmark-what-drove-lithium-prices-in-december/ (accessed: February 2018).

Jaskula, B. W., 2009. *Lithium*, *Mineral Commodity Summaries*. Reston, USA. Available at: http://minerals.usgs.gov/minerals/pubs/commodity/lithium/mcs-2009-lithi.pdf.

Jaskula, B. W., 2010. *Lithium*, *Mineral Commodity Summaries*. Reston, USA. Available at: https://minerals.usgs.gov/minerals/pubs/commodity/lithium/mcs-2010-lithi.pdf.

Jaskula, B. W., 2016. *Lithium*, *Mineral Commodity Summaries*. Reston, USA. Available at: https://minerals.usgs.gov/minerals/pubs/commodity/lithium/mcs-2016-lithi.pdf.

Jaskula, B. W., 2017. *Lithium*, *Mineral Commodity Summaries*. Reston, USA. Available at: https://minerals.usgs.gov/minerals/pubs/commodity/lithium/.

Jaskula, B. W., 2018. *Lithium*, *Mineral Commodity Summaries*. Reston, USA. Available at: https://minerals.usgs.gov/minerals/pubs/commodity/lithium/mcs-2018-lithi.pdf.

Katrivanos, F. C., 2016. *Silver*, *Minerals Yearbook*. Reston, USA. Available at: http://minerals.usgs.gov/minerals/pubs/country/2012/myb3-2012-my.pdf.

Kelly, D. and Matos, G. R., 2016. *Historical Statistics for Mineral and Material Commodities in the United States*, *USGS*. Available at: https://minerals.usgs.gov/minerals/pubs/historical-statistics/ (accessed:

February 2018).

Kelly, T. D., Ober, J. A. and Jaskula, B. W., 2017. *Lithium Statistics*, *USGS*. Available at: https://minerals.usgs.gov/minerals/pubs/historical-statistics/ds140-lithi.xlsx (accessed: February 2018).

Kempton, W., 2016. Electric vehicles: Driving range, *Nature Energy*, vol. 1, no. 9, pp. 1–2.

Kesler, S. E., Gruber, P. W., Medina, P. A., Keoleian, G. A., Everson, M. P. and Wallington, T. J., 2012. Global lithium resources: Relative importance of pegmatite, brine and other deposits, *Ore Geology Reviews*. Elsevier B.V., vol. 48, pp. 55–69.

KIA, 2017. *Kia Soul EV Battery*, *www.kia.com*. Available at: https://www.kia.com/us/en/content/ev-faqs_2016/charging/battery (accessed: December 2017).

KPMG International, 2017. *Global Automotive Executive Survey 2017*. Available at: https://assets.kpmg.com/content/dam/kpmg/xx/pdf/2017/01/.

Kuck, P. H., 1999. *Metal prices in the United States through 1998 - Nickel*, *USGS*. Reston, USA. Available at: https://minerals.usgs.gov/minerals/pubs/commodity/nickel/500798.pdf.

Kunasz, I. A., 2006. *Lithium resources*, *Industrial Minerals and Rocks*.

Kushnir, D. and Sandén, B. A., 2012. The time dimension and lithium resource constraints for electric vehicles, *Resources Policy*, vol. 37, no. 1, pp. 93–103.

Kuznets, S., 1955. Economic growth and income inequality, *The American economic review*. JSTOR, vol. 45, no. 1, pp. 1–28.

Lache, R., Galves, D., Nolan, P., Toulemonde, G., Gehrke, J., Sanger, K., Ha, V., Rao, S. and Cran, J., 2008. *Electric cars: Plugged in*, *Deutsche Bank*. New York. Available at: www.libralato.co.uk/docs/Electric_Cars_Plugged_In_Deutsche_Bank.pdf.

Lagowski, K., 2017. *What You Should Know About Today's Electric Car*

Batteries, *fleetcarma.com*. Available at: https://www.fleetcarma.com/todays-electric-car-batteries/ (accessed: December 2015).

Larcher, D. and Tarascon, J.-M., 2015. Towards greener and more sustainable batteries for electrical energy storage., *Nature chemistry*, vol. 7, no. 1, pp. 19–29.

Leccy, 2017. *EV charge time calculator*, *leccy.net*. Available at: https://leccy.net/ (accessed: December 2017).

Lewis, G. N. and Keyes, F. G., 1913. The potential of the lithium electrode, *Journal of the American Chemical Society*, vol. 35, no. 4, pp. 340–344.

Lichacz, W., 2007. *Exposing the Uranium Cartel in 1976*, *Friends of the Earth Australia*. Available at: http://www.foe.org.au/anti-nuclear/issues/oz/u/cartel (accessed: February 2018).

LME, 2018. *London Metal Exchange: LME Cobalt*, *London Metal Exchange*. Available at: https://www.lme.com/Metals/Minor-metals/Cobalt#tabIndex=0 (accessed: February 2018).

Loferski, P. J., 2018. *Platinum-Group Metals*. Reston, USA. Available at: https://minerals.usgs.gov/minerals/pubs/commodity/platinum/myb1-2012-plati.pdf.

Lu, H., Ma, H., Sun, Z. and Wang, J., 2017. Analysis and Prediction on Vehicle Ownership Based on an Improved Stochastic Gompertz Diffusion Process, *Journal of Advanced Transportation*, pp. 1–8.

Lu, L., Han, X., Li, J., Hua, J. and Ouyang, M., 2013. A review on the key issues for lithium-ion battery management in electric vehicles, *Journal of Power Sources*. Elsevier B.V, vol. 226, pp. 272–288.

Lukoil, 2016. *Major Trends in Global Oil Market to 2030*. Available at: http://www.lukoil.ru/FileSystem/PressCenter/78037.pdf.

Luo, X., Wang, J., Dooner, M. and Clarke, J., 2014. Overview of current development in electrical energy storage technologies and the application potential in power system operation, *Applied Energy*. Elsevier Ltd, vol. 137, pp. 511–536.

Machacek, E. and Fold, N., 2014. Alternative value chains for rare earths: The anglo-deposit developers, *Resources Policy*. Elsevier, vol. 42, pp. 53–64.

Macquarie Research, 2016. *Global Lithium Report Fully charged, but no shortage*. Available at: http://newagemetals.com/wp-content/uploads/MacquarieGlobalLithiumReport310516e245188.pdf.

Mahon, R. and McBride, S., 2009. Standardizing and disseminating knowledge: The role of the OECD in global governance, *European Political Science Review*. Cambridge University Press, vol. 1, no. 1, pp. 83–101.

Malenbaum, W., 1973. *World Resources for the Year 2000*, *The Annals of The American Academy*. Philadelphia.

Malenbaum, W., 1978. *World demand for raw materials in 1985 and 2000*. E/Mj Mining Informational Services.

Manzetti, S. and Mariasiu, F., 2015. Electric vehicle battery technologies: From present state to future systems, *Renewable and Sustainable Energy Reviews*. Elsevier, vol. 51, pp. 1004–1012.

Mardones, J., Silva, E. and Martínez, C., 1985. The copper and aluminum industries, *Resources Policy*, vol. 11, no. 1, pp. 3–16.

Martin, D., 1981. *Suit ended on supplies of uranium*, *The New York Times*. Available at: http://www.nytimes.com/1981/01/30/business/suit-ended-on-supplies-of-uranium.html (accessed: February 2018).

Martin, G., Rentsch, L., Höck, M. and Bertau, M., 2017. Lithium market research – global supply, future demand and price development, *Energy Storage Materials*. Elsevier, vol. 6, pp. 171–179.

Massari, S. and Ruberti, M., 2013. Rare earth elements as critical raw materials: Focus on international markets and future strategies, *Resources Policy*. Elsevier, vol. 38, no. 1, pp. 36–43.

Mauger, A. and Julien, C. M., 2017. Critical review on lithium-ion batteries: are they safe? Sustainable?, *Ionics*. Ionics, vol. 23, no. 8, pp. 1933–1947.

Maxwell, P., 2015. Transparent and opaque pricing: The interesting case of lithium, *Resources Policy*. Elsevier, vol. 45, pp. 92–97.

Meeus, M. and Scoyer, J., 2012. Advanced battery materials, in Sehrt, U. (ed.) *Precious Metals Handbook*. Umicore AG & Co KG, Hanau-Wolfgang, Germany.

Metalary, 2017. *Lithium Price*, *www.metalary.com*. Available at: https://www.metalary.com/lithium-price/ (accessed: February 2018).

Mianping, Z., Jiayou, T., Junying, L. and Fasheng, Z., 1993. Chinese saline lakes, *Hydrobiologia*, vol. 267, no. 1–3, pp. 23–36.

Miller, P., 2015. Automotive lithium-ion batteries, *Johnson Matthey Technology Review*, vol. 59, no. 1, pp. 4–13.

Mizushima, K., Jones, P. C., Wiseman, P. J. and Goodenough, J. B., 1980. LixCoO2 (0< x≤-1): A new cathode material for batteries of high energy density, *Materials Research Bulletin*, vol. 15, no. 6, pp. 183–789.

Mohr, D., Muller, N., Krieg, A., Gao, P., Kaas, H. W., Krieger, A. and Hensley, R., 2013. *The road to 2020 and beyond: What's driving the global automotive industry?*, *McKinsey & Company*. Available at: https://www.mckinsey.com/industries/high-tech/our-insights/disruptive-trends-that-will-transform-the-auto-industry.

Mohr, S., Höök, M., Mudd, G. and Evans, G., 2011. Projection of long-term paths for Australian coal production: Comparisons of four models, *International Journal of Coal Geology*. Elsevier B.V., vol. 86, no. 4, pp. 329–341.

Moncrief, W. A. B., 2010. Energy Storage – Applications in the Smart Grid, *Modern Electric Power Systems*, pp. 1–9.

Mudd, G. M., 2014. The future of Yellowcake: A global assessment of uranium resources and mining, *Science of the Total Environment*. Elsevier B.V., vol. 472, pp. 590–607.

Murphy, D. W. and Trumbore, F. a, 1976. The Chemistry of TiS and NbSe Cathodes, *Journal of electrochemical society*, vol. 123, no. 7, pp. 960–964.

Mwasilu, F., Justo, J. J., Kim, E. K., Do, T. D. and Jung, J. W., 2014. Electric vehicles and smart grid interaction: A review on vehicle to grid and renewable energy sources integration, *Renewable and Sustainable Energy Reviews*. Elsevier, vol. 34, pp. 501–516.

Navigant Research, 2017. *Global Energy Capacity for Advanced Batteries for Utility-Scale Energy Storage is Expected to Reach 42.7 GWh by 2025*, *www.navigantresearch.com*. Available at: https://www.navigantresearch.com/newsroom/global-energy-capacity-for-advanced-batteries-for-utility-scale-energy-storage-is-expected-to-reach-42-7-gwh-by-2025 (accessed: March 2018).

Needell, Z. A., McNerney, J., Chang, M. T. and Trancik, J. E., 2016. Potential for widespread electrification of personal vehicle travel in the United States, *Nature Energy*, vol. 1, no. 9.

Nemaska Lithium, 2018. *Nemaska Lithium Releases 2018 Feasibility Study*, *http://www.nemaskalithium.com*. Available at: http://www.nemaskalithium.com/en/investors/press-releases/2018/2383c40c-3570-49e0-86f5-9df5112a253c/ (accessed: February 2018).

Nickless, E., 2017. Resourcing Future Generations: A Contribution by the Earth Science Community, *Natural Resources Research*. Springer US, pp. 1–16.

Nishi, Y., 2001. The development of lithium ion secondary batteries, *The Chemical Record*, vol. 1, no. 5, pp. 406–413.

Nitta, N., Wu, F., Lee, J. T. and Yushin, G., 2015. Li-ion battery materials: Present and future, *Materials Today*. Elsevier Ltd., vol. 18, no. 5, pp. 252–264.

Nordhaus, W. D., 1977. Economic Growth and Climate: The Carbon Dioxide Problem, *American Economic Review*, vol. 67, no. 1, pp. 341–346.

Nykvist, B. and Nilsson, M., 2015. Rapidly falling costs of battery packs for electric vehicles, *Nature Climate Change*, vol. 5, no. 4, pp. 329–332.

Ober, J., 2000. *Lithium*, *Mineral Commodity Summaries*. Reston, USA. Available at: https://minerals.usgs.gov/minerals/pubs/commodity/lithium/450400.pdf.

Ober, J. A., 1998. *Lithium*, *Mineral Commodity Summaries*. Reston, USA. Available at: https://minerals.usgs.gov/minerals/pubs/commodity/lithium/.

Ober, J. A., 2007. *Lithium*, *Mineral Commodity Summaries*. Reston, USA. Available at: https://minerals.usgs.gov/minerals/pubs/commodity/lithium/lithimcs07.pdf.

OECD, 2014. *Cities and climate change: national governments enabling local action*, *www.oecd.org*. Available at: https://www.oecd.org/env/cc/Cities-and-climate-change-2014-Policy-Perspectives-Final-web.pdf%5Cn.

OECD, 2016. *GDP Long-term Forecast*, *www.oecd.org*. Available at: https://data.oecd.org/ (accessed: December 2017).

OICA, 2017. *Production Statistics*, *Organisation Internationale des Constructeurs d'Automobiles*. Available at: http://www.oica.net/category/production-statistics/ (accessed: December 2017).

Oliveira, L., Messagie, M., Rangaraju, S., Sanfelix, J., Hernandez Rivas, M. and Van Mierlo, J., 2015. Key issues of lithium-ion batteries - From resource depletion to environmental performance indicators, *Journal of Cleaner Production*. Elsevier Ltd, vol. 108, pp. 354–362.

Olivetti, E. A., Ceder, G., Gaustad, G. G. and Fu, X., 2017. Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals, *Joule*. Elsevier Inc., vol. 1, no. 2, pp. 229–243.

Palacín, M. R., 2009. Recent advances in rechargeable battery materials: a chemist's perspective, *Chemical Society Reviews*, vol. 38, no. 9, pp. 2565–2575.

Panasonic, 2011. *NCR18650 Lithium Ion Data Sheet*, *panasonic.com*. Available at: https://na.industrial.panasonic.com/products/batteries/rechargeable-batteries/lithium-ion/series/cylindrical-series/ (accessed: October 2017).

Panasonic, 2012a. *NCR18650A Lithium Ion Data Sheet*, *panasonic.com*. Available at: https://na.industrial.panasonic.com/products/batteries/rechargeable-batteries/lithium-ion/series/cylindrical-series/ (accessed: October 2017).

Panasonic, 2012b. *NCR18650B Lithium Ion Data Sheet*, *panasonic.com*. Available at: https://na.industrial.panasonic.com/products/batteries/rechargeable-batteries/lithium-ion/series/cylindrical-series/ (accessed: October 2017).

Panasonic, 2012c. *NCR18650F Lithium Ion Data Sheet*, *panasonic.com*. Available at: https://na.industrial.panasonic.com/products/batteries/rechargeable-batteries/lithium-ion/series/cylindrical-series/ (accessed: October 2017).

Patiño Douce, A. E., 2016. Metallic Mineral Resources in the Twenty-First Century. I. Historical Extraction Trends and Expected Demand, *Natural Resources Research*, vol. 25, no. 1, pp. 71–90.

Peiró, L. T., Méndez, G. V. and Ayres, R. U., 2013. Lithium: Sources, production, uses, and recovery outlook, *Jom*, vol. 65, no. 8, pp. 986–996.

Petroff, A., 2017. *These countries want to ban gas cars*, *CNN*. Available at: http://money.cnn.com/2017/09/11/autos/countries-banning-diesel-gas-cars/index.html (accessed: January 2018).

Phillips, W. G. ., 1977. Statistical estimation of global mineral resources, *Resources Policy*, vol. 3, no. 4, pp. 268–280.

Platts, 2017. *Lithium supply to outweigh demand by 2018, cobalt to remain tight: CRU*, *www.platts.com*. Available at: https://www.platts.com/latest-news/metals/dublin/lithium-supply-to-outweigh-demand-by-2018-cobalt-26720886 (accessed: March 2018).

Plug-in America, 2017. *Model S Survey Data Overview*, *pluginamerica.org*. Available at: https://survey.pluginamerica.org/model-s/charts.php (accessed: December 2017).

Pool, T., 2013. Uranium Supply, Demand and Prices, in *IAEA Technical Meeting*. International Atomic Energy Agency, Vienna, Austria, p. 29. Available at: https://www.iaea.org/OurWork/ST/NE/NEFW/Technical-Areas/NFC/documents/uranium/tm-isl-2013/02.Pool_2013_U_supply_demand_prices.pdf.

Poullikkas, A., 2013. A comparative overview of large-scale battery systems for electricity storage, *Renewable and Sustainable Energy Reviews*. Elsevier, vol. 27, pp. 778–788.

Quist-Jensen, C., Macedonio, F. and Drioli, E., 2016. Integrated Membrane Desalination Systems with Membrane Crystallization Units for Resource Recovery: A New Approach for Mining from the Sea, *Crystals*, vol. 6, no. 4, pp. 1–36.

Radetzki, M., 2013. The relentless progress of commodity exchanges in the establishment of primary commodity prices, *Resources Policy*. Elsevier, vol. 38, no. 3, pp. 266–277.

Rankin, W. J., 2011. *Minerals, metals and sustainability: meeting future material needs*. CSIRO publishing, Boca Raton, USA.

REN21, 2017. *Renewables 2017: global status report*, *Renewable and Sustainable Energy Reviews*. Paris, France. Available at: http://www.ren21.net/wp-content/uploads/2017/06/17-8399_GSR_2017_Full_Report_0621_Opt.pdf%0Ahttp://dx.doi.org/10.1016/j.rser.2016.10.049%0Ahttp://www.ren21.net/status-of-renewables/global-status-report/.

Reuters, 2017. *Albemarle asks Chile to raise lithium production limit*, *Reuters*. Available at: https://www.reuters.com/article/chile-lithium-albemarle/albemarle-asks-chile-to-raise-lithium-production-limit-idUSL2N1LW1LP (accessed: January 2018).

Risacher, F., Alonso, H. and Salazar, C., 2003. The origin of brines and salts in Chilean salars: A hydrochemical review, *Earth-Science Reviews*, vol. 63, no. 3–4, pp. 249–293.

Robbins, L., 1932. *An essay on the nature and significance of economic science*. 1st edn. Macmillan & Co., Limited, London, United Kingdom.

Roberts, M. C., 1992. The material composition of product and new materials, *Resources Policy*, vol. 18, no. 2, pp. 122–136.

Rogelj, J., Elzen, M. Den, Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K. and Meinshausen, M., 2016. Perspective : Paris Agreement climate proposals need boost to keep warming well below 2° C, *Nature Climate Change*. Nature Publishing Group, vol. 534, no. June, pp. 631–639.

Sanderson, H., 2017. *LME considers starting lithium contract to tap electric car boom*, *Financial Times*. Available at: https://www.ft.com/content/24c36964-89af-11e7-bf50-e1c239b45787 (accessed: February 2018).

Sanderson, H., 2018. *Lithium prices to fall 45% by 2021, Morgan Stanley says*, *Financial Times*. Available at: https://www.ft.com/content/66012fe2-1ae1-11e8-aaca-4574d7dabfb6 (accessed: March 2018).

Schoenung, S. M. and Eyer, J., 2008. *Benefit / Cost Framework for Evaluating Modular Energy Storage A Study for the DOE Energy Storage Systems Program*, *Sandia National Laboratories*. Albuquerque, USA. Available at: https://www.osti.gov/scitech/biblio/1028917.

Scrosati, B. and Garche, J., 2010. Lithium batteries: Status, prospects and future, *Journal of Power Sources*, vol. 195, no. 9, pp. 2419–2430.

Seyhan, D., Weikard, H. P. and Van Ierland, E., 2012. An economic model of long-term phosphorus extraction and recycling, *Resources, Conservation and Recycling*. Elsevier B.V., vol. 61, pp. 103–108.

Shanghai Metals Market, 2017. *Lithium Carbonate News and Price Analysis*, *www.metal.com*. Available at: http://original.metal.com/metals/productinfo/201102250059 (accessed: February 2018).

Shanghai Metals Market, 2018. *Lithium Carbonate*, *original.metal.com*. Available at: http://original.metal.com/metals/productinfo/201102250059 (accessed: February 2018).

Shedd, K. B., 1999. *Metal prices in the United States through 1998 - Cobalt*. Reston, USA. Available at: https://minerals.usgs.gov/minerals/pubs/commodity/cobalt/210798.pdf.

Shedd, K. B., 2018. *Cobalt*, *Mineral Commodity Summaries*. Reston, USA. Available at: https://minerals.usgs.gov/minerals/pubs/commodity/cobalt/mcs-2018-cobal.pdf.

Skene, K. and Murray, A., 2017. *Sustainable Economics: Context, Challenges and Opportunities for the 21st-century Practitioner*. 1st edn. Routledge.

Skinner, B. J., 1976. Second iron age ahead, *American Journal of Science*. Yale Univ., New Haven, vol. 64, no. 3.

Skinner, B. J., 2001. Exploring the Resource Base, in *Conference on Depletion and the Long-Run Availability of Mineral Commodities*. www.rff.org, Washington, USA, p. 25. Available at: http://www.rff.org/files/sharepoint/WorkImages/Download/RFF-Event-April01-keynote.pdf.

Smith, G. D., 1988. *From Monopoly to Competition, the Transformation of Alcoa, 1888-1986*. 1st edn. Cambridge University Press.

Sonoc, A., Jeswiet, J. and Soo, V. K., 2015. Opportunities to Improve Recycling of Automotive Lithium Ion Batteries, in *The 22nd CIRP conference on Life Cycle Engineering Opportunities*. Elsevier B.V., pp. 752–757.

Speirs, J., Contestabile, M., Houari, Y. and Gross, R., 2014. The future of lithium availability for electric vehicle batteries, *Renewable and Sustainable Energy Reviews*. Elsevier, vol. 35, pp. 183–193.

Spulber, A. and Dennis, E. P., 2016. *Auto Dealerships : Destined for Disruption*, *Center for Automotive Research*. Michigan, USA. Available at: https://www.bbvaresearch.com/wp-content/uploads/2016/02/160224_US_AutoDisruption.pdf.

SQM, 2018. *SQM informs about meeting with CORFO*. Santiago, Chile. Available at: http://s1.q4cdn.com/793210788/files/doc_news/2018/PR_Corfo_17jan2018_ing.pdf.

Suslick, S. B. and Harris, D. P., 1990. Long-range metal consumption forecasts using innovative methods, *Resources Policy*, vol. 16, no. 3, pp. 184–199.

Sverdrup, H. U., 2016. Modelling global extraction, supply, price and depletion of the extractable geological resources with the LITHIUM model, *Resources, Conservation and Recycling*. Elsevier B.V., vol. 114, pp. 112–129.

Swain, B., 2017. Recovery and recycling of lithium: A review, *Separation and Purification Technology*. Elsevier B.V., vol. 172, no. November, pp. 388–403.

Swain, H., 2017. *Why Canada supported a uranium cartel*, *The Globe and Mail*. Available at: https://www.theglobeandmail.com/report-on-business/economy/economy-lab/why-canada-supported-a-uranium-cartel/article615837/ (accessed: February 2018).

Tahil, W., 2008. *The trouble with lithium 2: Under the microscope*, *Meridian international research*. Martainville, France. Available at: http://www.meridian-int-res.com/Projects/Lithium_Microscope.pdf.

Tahil, W., 2010. *How Much Lithium does a Li-ion EV battery really need?*, *Meridian International Research*. Martainville, France. Available at: http://www.meridian-int-res.com/Projects/How_Much_Lithium_Per_Battery.pdf.

Tan, K. M., Ramachandaramurthy, V. K. and Yong, J. Y., 2016. Integration of electric vehicles in smart grid: A review on vehicle to grid technologies and optimization techniques, *Renewable and Sustainable Energy Reviews*. Elsevier, vol. 53, pp. 720–732.

Tesla, 2017. *Vehicle Warranty*, *www.tesla.com*. Available at: https://www.tesla.com/support/vehicle-warranty (accessed: December 2017).

The Economist, 2017. *Electric vehicles powered by fuel-cells get a second look*, *www.economist.com*. Los Angeles. Available at:

https://www.economist.com/news/science-and-technology/21727776-electric-vehicles-be-powered-fuel-cells-rather-batteries-show-way-ahead-batteries (accessed: January 2018).

The Society for Mining Metallurgy and Exploration Inc., 2014. *The 2014 SME Guide*. Englewood, USA. Available at: http://www.crirsco.com/docs/2014_sme_guide_ june_10_2014_appendix_a_update_march_2016.pdf.

Tianqi Lithium, 2017. *Tianqi Lithium*, *www.tianqilithium.com*. Available at: http://www.tianqilithium.com/en/index.aspx (accessed: January 2018).

Tilton, J. E., 1996. Exhaustible resources and sustainable development: Two different paradigms, *Resource Policy*, vol. 22, no. 96, pp. 91–97.

Tilton, J. E., 2003. Assessing the threat of mineral depletion, *Minerals and Energy*, vol. 18, no. 1, pp. 33–42.

Tilton, J. E. and Guzmán, J. I., 2016. *Mineral Economics and Policy*. 1st edn. RFF Press, New York, USA.

Tilton, J. E. and Skinner, B. J., 1987. The meaning of resources, *Resources and world development*. Wiley New York, pp. 13–27.

Tolcin, A., 2013. *Indium*, *Minerals Yearbook*. Reston, USA. Available at: https://minerals.usgs.gov/minerals/pubs/commodity/indium/myb1-2011-indiu.pdf.

Topp, V., Bloch, H., Soames, L. and Parhan, D., 2008. *Productivity in the Mining Industry : Measurement and Interpretation*, *Productivity Commission Staff Working Paper*. Commonwealth of Australia, Melbourne, Australia.

UNECE, 1979. *1979 Convention On Long-Range Transboundary Air Pollution*. Geneva, Switzerland. Available at: https://www.unece.org/fileadmin/DAM/env/lrtap/full text/1979.CLRTAP.e.pdf%0Ahttp://www.unece.org/env/lrtap/lrtap_h1.html.

UNFCCC, 2014. *United Nations Climate Change*, *unfccc.int*. Available at:

http://unfccc.int/2860.php (accessed: January 2018).

United Nations, 2017. *World Population Prospects 2017*, *United Nations*. Available at: https://esa.un.org/unpd/wpp/ (accessed: December 2017).

US Department of Energy, 2016. *DOE Global Energy Storage Database*, *energystorageexchange.org*. Available at: www.energystorageexchange.org/projects/data_visualization (accessed: January 2018).

US Department of Labor, 2017. *CPI Data*, *bls.gov*. Available at: https://www.bls.gov/cpi/data.htm (accessed: February 2018).

USGS, 2012. *Metal Prices in the United States Through 2010*, *Pubs.Usgs.Gov*. Reston, USA. Available at: http://pubs.usgs.gov/sir/2012/5188/.

Vikström, H., Davidsson, S. and Höök, M., 2013. Lithium availability and future production outlooks, *Applied Energy*, vol. 110, pp. 252–266.

Wagner, M. and Wellmer, F.-W., 2009. A hierarchy of natural resources with respect to sustainable development—A basis for a natural resources efficiency indicator, in Richards, J. (ed.) *Mining, society, and a sustainable world*. 2nd edn. Springer, pp. 91–121.

Wang, X., Gaustad, G., Babbitt, C. W. and Richa, K., 2014. Economies of scale for future lithium-ion battery recycling infrastructure, *Resources, Conservation and Recycling*. Elsevier B.V., vol. 83, pp. 53–62.

Wanger, T. C., 2011. The lithium future: resources, recycling, and the environment, *Conservation Letters*, vol. 4, no. 3, pp. 202–206.

Whittingham, M. S., 1978. Chemistry of intercalation compounds: Metal guests in chalcogenide hosts, *Progress in Solid State Chemistry*, vol. 12, no. 1, pp. 41–99.

Wilson, T. and Biesheuvel, T., 2017. *Mad Scramble for Lithium Mines Stretches From Congo to Cornwall* | *Bloomberg New Energy Finance*, *Bloomberg New Energy Finance*. Available at: https://about.bnef.com/blog/mad-scramble-for-lithium-mines-stretches-from-congo-to-cornwall/ (accessed: February 2018).

Wolfram, P. and Lutsey, N., 2016. *Electric vehicles: Literature review of technology costs and carbon emissions*. 14. Available at: https://www.theicct.org/sites/default/files/publications/ICCT_LitRvw_EV-tech-costs_201607.pdf.

World Bank, 2017. *Data Catalog*, *World Bank*. Available at: https://data.worldbank.org/data-catalog/ (accessed: December 2017).

World Energy Council, 2013. *World Energy Scenarios: Composing energy futures to 2050*. London, United Kingdom. Available at: https://www.worldenergy.org/wp-content/uploads/2013/09/World-Energy-Scenarios_Composing-energy-futures-to-2050_Full-report.pdf.

World Energy Council, 2016. *World Energy Resources - E-Storage*, *World Energy Council Report*. Available at: https://www.worldenergy.org/wp-content/uploads/2017/03/WEResources_E-storage_2016.pdf%0Ahttp://www.worldenergy.org/wp-content/uploads/2013/09/Complete_WER_2013_Survey.pdf.

Worstall, T., 2013. *But Why Did Julian Simon Win The Paul Ehrlich Bet?*, *Forbes*. Available at: https://www.forbes.com/sites/timworstall/2013/01/13/but-why-did-julian-simon-win-the-paul-ehrlich-bet/#6a08b4d81b03 (accessed: March 2018).

Yaksic, A. and Tilton, J. E., 2009. Using the cumulative availability curve to assess the threat of mineral depletion: The case of lithium, *Resources Policy*, vol. 34, no. 4, pp. 185–194.

Yap, C.-W., 2015. *China Ends Rare-Earth Minerals Export Quotas*, *The Wall Street Journal*. Available at: https://www.wsj.com/articles/china-ends-rare-earth-minerals-export-quotas-1420441285 (accessed: February 2018).

Yoshino, A., 2012. The birth of the lithium-ion battery, *Angewandte Chemie - International Edition*, vol. 51, no. 24, pp. 5798–5800.

Zakeri, B. and Syri, S., 2015. Electrical energy storage systems: A comparative life cycle cost analysis, *Renewable and Sustainable Energy Reviews*. Elsevier, vol. 42, pp. 569–596.

Zeng, X., Li, J. and Singh, N., 2014. Recycling of spent lithium-ion battery: A critical review, *Critical Reviews in Environmental Science and Technology*, vol. 44, no. 10, pp. 1129–1165.